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Suppression Methods for Deep Seated Coal Fires

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16. Abstract

This study was a joint U.S. Coast Guard /Maritime Administration effort to identify fire prevention and/or suppression techniques for spontaneously induced coal cargo fires. The four test series conducted investigated spontaneous ignition, permeation, fire quench, and coal column fire characteristics. The spontaneous ignition tests identified variables that could be controlled in an attempt to prevent combustion. Results showed spontaneous ignition difficult to predict and, therefore, control. The permeation studies evaluated carbon dioxide and nitrogen as suppression agents. Results indicated the retention time of nitrogen in a coal pile to be far greater than the retention time of carbon dioxide. The fire quench tests compared these agents applied to a hot fire. Results showed both equally effective at displacing oxygen. The coal column tests applied these agents to a deep-seated fire at different locations. Results supported those of the permeation studies and showed mid-level injection of the agents to be most effective. Thus, the study indicates a portable system that applies nitrogen to the middle of the coal pile to be most effective. Large-scale work should be done to verify this. Keywords:

17. Key Words

coal, coal fires, carbon dioxide, nitrogen, suppression, permeation, injection, coal colliers

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Conversions to Metric Measures

When you know (symbol)	Multiply by	To find (symbol)
Length		
inches (in)	2.540	centimeters (cm)
feet (ft)	30.48	centimeters (cm)
feet (ft)	0.3048	meters (m)
Area		
square inches (in^2)	6.452	square centimeters (cm^2)
square feet (ft^2)	929.0	square centimeters (cm^2)
square feet (ft^2)	0.09290	square meters (m^2)
Volume		
fluid ounces, US (fl oz)	29.57	milliliters (ml); cubic centimeters (cm^3)
gallons, US liquid (gal)	3.785	liters (l)
cubic feet (ft^3)	0.02832	cubic meters (m^3)
cubic yards (yd^3)	0.7646	cubic meters (m^3)
Mass (weight)		
ounces, avoirdupois (oz)	28.35	grams (g)
pounds (lb)	0.4536	kilograms (kg)
Density		
pounds per cubic inch (lb/in^3)	27.68	grams per cubic centimeter (g/cm^3)
pounds per cubic foot (lb/ft^3)	16.02	kilograms per cubic meter (kg/m^3)
Pressure		
pounds per square inch (psi)	6895	pascals (Pa); newtons per square meter (N/m^2)
pounds per square inch (psi)	0.0703	kilograms per square centimeter (kg/cm^2)
pounds per square inch (psi)	51.71	millimeters of mercury (mm Hg) at 0°C
pounds per square inch (psi)	0.06895	bars (10^5 N/m^2)
inches of water (in H_2O) at 60°F	1.867	millimeters of mercury (mm Hg) at 0°C
inches of water (in H_2O) at 60°F	248.9	pascals (Pa)
inches of water (in H_2O) at 60°F	0.002489	bars (10^5 N/m^2)
inches of mercury (in Hg) at 32°F	3386	pascals (Pa)
inches of mercury (in Hg) at 32°F	0.03386	bars (10^5 N/m^2)
Energy		
British thermal units (Btu)	1055	joules (J); newton-meter (Nm)
British thermal units (Btu)	0.2520	kilocalories (kcal)
Thermal Conductance		
Btu / hr - ft^2 - °F	0.0001356	calories / sec - cm^2 - °C
Btu / hr - ft^2 - °F	0.4882	calories / hr - cm^2 - °C
Btu / hr - ft^2 - °F	0.0005678	watts / cm^2 - °C
Heat Flow		
Btu / hr - ft^2	0.00007535	calories / sec - cm^2
Btu / hr - ft^2	0.2712	calories / hr - cm^2
Btu / hr - ft^2	0.0003154	watts / cm^2

Fahrenheit Temperature

Celsius Temperature

Conversions from Metric Measures

When you know (symbol)	Multiply by	To find (symbol)
Length		
millimeters (mm)	0.03937	inches (in)
centimeters (cm)	0.3937	inches (in)
meters (m)	39.37	inches (in)
Meters (m)	3.281	feet (ft)
Area		
square centimeters (cm^2)	0.1550	square inches (in^2)
square centimeters (cm^2)	0.001076	square feet (ft^2)
square meters (m^2)	1550	square inches (in^2)
square meters (m^2)	10.76	square feet (ft^2)
square meters (m^2)	1.196	square yards (yd^2)
Volume		
milliliters (ml)	0.03381	fluid ounces, US (fl oz)
liters (l)	0.2642	gallons, US liquid (gal)
liters (l)	0.03531	cubic feet (ft^3)
cubic centimeters (cm^3)	0.06102	cubic inches (in^3)
cubic meters (m^3)	35.31	cubic feet (ft^3)
cubic meters (m^3)	1.308	cubic yards (yd^3)
Mass (weight)		
grams (g)	0.03527	ounces, avoirdupois (oz)
grams (g)	0.002205	pounds (lb)
kilograms (kg)	2.205	pounds (lb)
Density		
grams per cubic centimeter (g/cm^3)	0.03613	pounds per cubic inch (lb/in^3)
kilograms per cubic meter (kg/m^3)	0.06243	pounds per cubic foot (lb/ft^3)
Pressure		
pascals (Pa); newtons per sq. meter (N/m^2)	0.000145	pounds per square inch (psi)
bars (10^5 N/m^2)	14.50	pounds per square inch (psi)
kilograms per square centimeter (kg/cm^2)	14.22	pounds per square inch (psi)
millimeters of mercury (mm Hg) at 0°C	0.01934	pounds per square inch (psi)
millimeters of mercury (mm Hg) at 0°C	0.5357	inches of water (in H_2O) at 60°F
bars (10^5 N/m^2)	401.8	inches of water (in H_2O) at 60°F
pascals (Pa)	0.00402	inches of water (in H_2O) at 60°F
pascals (Pa)	0.000295	inches of mercury (in Hg) at 32°F
bars (10^5 N/m^2)	29.53	inches of mercury (in Hg) at 32°F
Energy		
kilojoules	0.9478	British thermal units (Btu)
kilocalories	3.968	British thermal units (Btu)
Thermal Conductance		
calories / sec - cm^2 - °C	7373	Btu / hr - ft^2 - °F
watts / cm^2 - °C	1761	Btu / hr - ft^2 - °F
Heat Flow		
calories / sec - cm^2	13270	Btu / hr - ft^2

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Denise Baird contributed significantly to this project. Her assistance in analyzing and presenting data for this report is appreciated.

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1.0 INTRODUCTION

"Since early September, coal experts from around the world have been struggling at Long Beach and Los Angeles harbors to cool down 189,000 tons of smoldering and burning coal inside the holds of four cargo ships. I can never recall an incident where there have been four ships on fire and in danger of sinking anywhere in the world," said James McJunkin, executive director of the Port of Long Beach, where three of the ships are docked[1]. This incident was the culmination of a problem that began in 1977 when oil prices doubled. As the price of oil climbed, industries converted to coal. This resulted in a dramatic increase in coal exports. The following table lists the amount of coal exported and the number of fires and explosions reported on coal colliers.

TABLE 1-1. FIRE LOSSES FOR COAL SHIPPING

Year	U.S. Coal Export[2] (million short tons)	Reports of World Shipping Losses[3] (fires and explosions)
1977	54.3	2
1978	40.7	2
1979	66.0	4
1980	91.7	10
1981	112.5	24

The table shows that while there was a two-fold increase in U.S. coal exports from 1977 through 1981, there was a 12-fold increase in the number of fires and explosions on vessels carrying coal as a cargo. Factors contributing to the rapid increase in the number of fires and explosions include an increase in lower grade coal exported, lack of precautions in storing and loading coal, and inadequate prevention measures once coal was loaded.

Deep seated coal fires are not a new problem. J. Dilley, survivor of the sinking of the TITANIC reported[4], "The TITANIC sailed from Southhampton on Wednesday, April 10, at noon. I was assigned to the TITANIC from the OCEANIC, where I had served as a fireman. From the day we sailed the TITANIC was on fire, and my sole duty, together with eleven other men, had been to fight that fire. We had made no headway against it."

"Of course, sir," he went on, "the passengers knew nothing of the fire. Do you think, sir, we'd have let them know about it? No, sir."

"The fire started in bunker No. 6. There were hundreds of tons of coal stored there. The coal on top of the bunker was wet, as all the coal should have been, but down at the bottom of the bunker the coal had been permitted to get dry."

"The dry coal at the bottom of the pile took fire, sir, and smoldered for days. The wet coal on top kept the flames from coming through, but down in the bottom of the bunker, sir, the flames was a-raging."

"Two men from each watch of stokers were told off, sir, to fight that fire. The stokers, you know, sir, work four hours at a time, so twelve of us was fighting flames from the day we put out of Southampton until we hit the iceberg."

"No, sir, we didn't get that fire out, and among the stokers there was talk, sir, that we'd have to empty the big coal bunkers after we'd put our passengers off in New York and then call on the fireboats there to help us put out the fire."

"But we didn't need such help. It was right under bunker No. 6 that the iceberg tore the biggest hole in the TITANIC, and the flood of water that came through, sir, put out the fire that our tons and tons of water had not been able to get rid of."

Since massive flooding of coal stored on a ship is not a viable option, the Coast Guard and the Maritime Administration (MARAD) joined in a cooperative effort to address the problem, concentrating on practical suppression methods for a coal fire at sea.

1.1 Objective

The objective of the program as stated in the agreement between the Coast Guard and MARAD was:

> Identify fire prevention and/or suppression techniques for spontaneously induced coal cargo fires in bulk carriers which are insensitive to the type or condition of the coal, and test and evaluate the two most promising techniques.

1.2 Suppression Methods

As a result of a literature search, suppression techniques were identified and then evaluated. These included securing the ventilation, providing excess ventilation, using steam lances, using additives, addition of wetting agents, using dry ice, flooding with water, and injecting inert gas.

The most direct and effective technique to suppress a coal fire is to secure the ventilation. This is difficult to do in practice on ships. The air space between the coal and hatch cover provides a ready source of available oxygen for the fire and the hatch covers do not make airtight seals. The technique of providing excess ventilation also works better in theory than in practice. If heat is removed faster than it is produced, there is no heat build-up and no fire. In practice, however, the small spaces in the closely packed coal allow little air movement and the heat can not be removed rapidly. The excess ventilation ends up supporting a fire rather than eliminating it.

The disadvantages of using steam lances outweigh the advantages. The theory behind steam lances involves coating the coal with a layer of water. The steam provides the energy to penetrate the coal and, as the steam hits the coal, it condenses to water, preventing the coal from igniting. The disadvantage is that this technique adds heat to the coal from the chemisorption of water.

Chemical inhibitors have been considered and used for some time. Inhibitors work to block the chemical chain reaction of combustion before it takes place. The problem with inhibitors is that they continue to act on the coal when it is being used, making it more difficult to ignite and lowering its heating value.

The addition of wetting agents to water has been used extensively in the fire industry to enhance fire extinguishing efforts. Wetting agents change the basic properties of water, so that it can easily penetrate densely packed layers of materials. This is a very effective means of fire extinguishment in most situations. It is not practical when dealing with coal, however, because many of the wetting agents affect coal adversely by penetrating the coal and lowering its heating value.

Dry ice has been found to lower the average temperatures in coal barges[5]. However, the blocks of dry ice must be added as the coal is being loaded, making this method a preventive measure instead of a response technique.

Water flooding is used in firefighting for a variety of applications. This is a fairly successful method, usually resulting in complete extinguishment. There are a couple of drawbacks, however. When water is injected into a deep-seated coal fire, there is a possibility that a steam explosion will occur. This is caused by water moving from the liquid to the gaseous phase too quickly. Steam explosions can be very dangerous and can cause considerable damage to the ship.

Even if the water doesn't go through a violent phase change, it can still do considerable damage to the inside of the ship. When water is mixed with burning coal, the result is an acidic solution that corrodes the inside of the cargo hold, potentially causing more damage than the smoldering fire.

The suppression method that appears to offer the most promise and fewest drawbacks is inert gas injection. An inert gas injected into a closed container will displace oxygen without presenting an explosive condition or causing a chemical reaction. It can be applied at the time a heating problem is discovered as well as being used as a preventive measure. Although any inert gas could be used, a gas that is economical, readily available and easily obtained would be most desirable. The two gases selected meeting these criteria were carbon dioxide and nitrogen. The literature search showed no research had been conducted on the application of these suppression methods to coal collier fires.

1.3 Coal

The coal used throughout this project was from Illinois Seam #6. The supplier of this coal was the lowest bidder who could supply the coal with the characteristics needed for spontaneous ignition. This coal is a highly volatile, C rank bituminous coal. Coals with these characteristics have a history of self-heating. The single most important factor in the tendency towards self-heating of coal is rank. Higher rank coal exhibits little or no heating, while lower rank coals frequently exhibit heating. Other factors contributing to self-heating are particle size, pyrite content of the coal, geological factors, and mining practices[6].

The Bureau of Mines, in a cooperative effort with the Coast Guard, analyzed the coal selected for the study. In addition, they evaluated the coal's self-heating potential. Their report is included as Appendix A. According to their size analysis 48.1 percent of the sample was greater than 470 microns, 40 percent was greater than 300 microns, and the remaining 7 percent less than 300 microns. The size analysis results are shown in Table 2 below.

TABLE 1-2. SIZE ANALYSIS OF COAL

Mesh Size	Weight (g)	Percent Passage
4	629.8	48.1
8	199.1	15.2
12	85.5	6.6
20	148.4	11.3
50	154.4	11.8
100	62.6	4.8
200	19.6	1.5
<200	9.2	0.7
	1309.2	100.0

The proximate and ultimate analysis results are shown in two tables in Appendix A. The moisture levels, both "as received" and "air dried," should be noted. The inherent moisture and the moisture in the air which is in contact with the coal plays a role in spontaneous heating[7]. The pyritic sulfur levels are also worth noting. Kim reports that coal with levels over 2 percent show a tendency towards self-heating[8]. In the case of Illinois Seam #6, pyritic sulfur is at 1.2 percent, not enough to affect self-heating, according to current literature.

Testing in the Bureau of Mines' adiabatic heating apparatus showed that the minimum self-heating tendency of coal from Illinois Seam #6 is 70°C (158°F), a moderate risk for self heating[9]. The Bureau of Mines also developed a model for the spontaneous ignition process. Figure 5 of Appendix A is a graph showing the time needed for thermal runaway based on this model. The graph illustrates that as the temperature increases, the time required for thermal runaway decreases.

2.0 SPONTANEOUS IGNITION TESTS

Spontaneous ignition was studied first in order to understand the process and develop a procedure to prevent its occurrence. Three variables, ventilation, humidity, and temperature were considered so important to the process of spontaneous combustion that they were controlled in this phase. These variables were controlled in an effort to create a situation where spontaneous combustion could be reproduced. If spontaneous combustion can be controlled, it can be prevented. The National Fire Protection Agency provides a list of precautions to assist in the prevention of spontaneous heating of coal[10].

Ventilation is important because it provides the oxygen necessary to sustain combustion. Oxygen is essential to the process of spontaneous combustion and to sustain the subsequent fire. If ventilation is poor and the oxygen level goes below 15 or 16 percent, the fire will enter a smoldering phase, producing large quantities of heat and gases. As long as there is at least 10 to 12 percent oxygen, the fire will smolder. Coal produces small amounts of oxygen during the weathering phase. This also helps to initiate and sustain combustion.

Humidity is also an important variable when considering the self-heating of coal. Coal, depending upon its characteristics, has the potential to oxidize rapidly. Carbon sites on the coal readily combine with oxygen and water. When coal becomes wet, the result is an exothermic reaction. The heat produced by this reaction is often enough to trigger spontaneous ignition. While coal that has some moisture is susceptible to heating, excessive amounts of moisture will prevent heating. It has been found that cycles of wetting and then drying the coal may accelerate spontaneous heating.

The surrounding temperatures, as well as the temperature within the coal pile, can profoundly affect self-heating. If outside temperatures are high, they may accelerate heating in the coal pile. At the same time, if heating is occurring within the pile, this heat may accumulate due to poor circulation in the pile itself. This heating will perpetuate itself until ignition occurs. Heat will also dry the coal, contributing to the wetting/drying cycle.

2.1 Small-Scale Test Chamber and Instrumentation

A small scale test chamber was designed to evaluate the effects of these variables. Two identical chambers were constructed which permitted twin tests to be run concurrently. Their internal dimensions were 1 meter by 1 meter by 1 meter (3.28 x 3.28 x 3.28 feet). Each chamber was constructed using 1/4-inch (0.63 cm) carbon steel plates. They were insulated with 3/4-inch (1.9 cm) Marinite boards, two boards thick, giving

a total thickness of 1-1/2 inches (3.81 cm). This was considered sufficient insulation to prevent heat loss through the walls of the chamber or any exchange between the chamber and outside atmosphere. The chambers were accessible from all six sides with 54 inches (137 cm) between the ground and the bottom of each chamber. The chambers are shown in Figure 2-1 with instrumentation for thermocouples, and ventilation equipment attached to the bottom of each.

The top of the chamber was fitted with two 4 x 8 inch (10.16 x 20.32 cm) adjustable air flow registers to provide adequate ventilation. The top opened to allow for hand loading of the coal. Figure 2-2 shows the top of the chamber with the vents visible. Pad eyes are on either side of the vents. Lines were attached to the pad eyes so that the tops could be opened without the necessity of standing over the chamber.

The bottom of each chamber could be dropped open, providing an easy means of removing the coal. Each was equipped with an 8-inch (20.32 cm) diameter vent, fitted with a collar so that an adjustable air duct could be attached. On the other end of the air duct was a fan providing forced ventilation. There were four 4-inch (10.16 cm) vents, one in each corner of the chambers, to provide additional natural ventilation. These four vents had removable covers. The bottom of the chamber was covered with a wire mesh to keep the coal from falling through the vents (see Figure 2-2). The large vent appears in the center, and the four smaller vents are in each corner.

A heating unit was housed in a metal sphere and placed slightly below center of the coal mass in the chamber. A metal rod was used to maintain the sphere's position in the center of the pile. The rod ran from the front of the chamber to the back. Figure 2-3 shows the heating sphere, looking from the bottom of the chamber (Note the steel rod supporting the heating sphere). The inner Marinite walls are also visible in this figure.

Temperature was measured using Type K inconel sheathed thermocouples. There were three strings, with ten thermocouples per string, placed on orthogonal axes. On each axis, a thermocouple was placed next to the heating sphere, with a thermocouple spaced every four inches (10.16 cm) out to the wall of the chamber. The heating sphere was placed 4 inches (10.16 cm) below center so there were 6 thermocouples above the ball and 4 below. The sphere was centered in the horizontal plain allowing 5 thermocouples on each side. Figure 2-4 shows the thermocouple placement inside and outside the chamber with the thermocouples along the supporting rod for the heating sphere in place.

Several other variables were considered important for predicting spontaneous combustion; methane, carbon monoxide, carbon dioxide, oxygen, air velocity, and smoke particulates. Methane is one of the products produced as a result of the

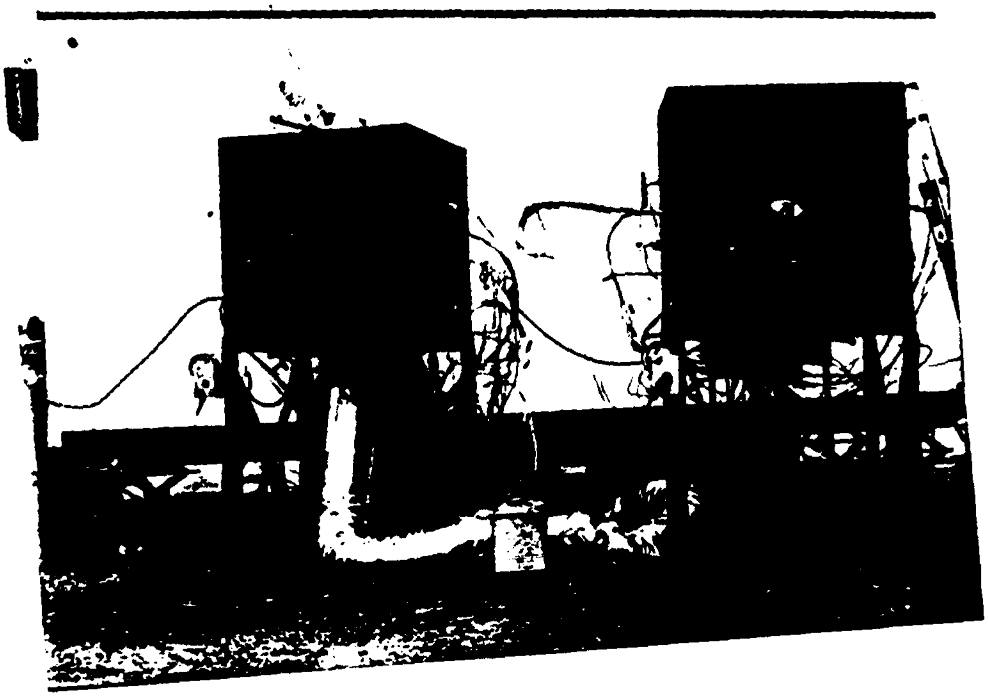
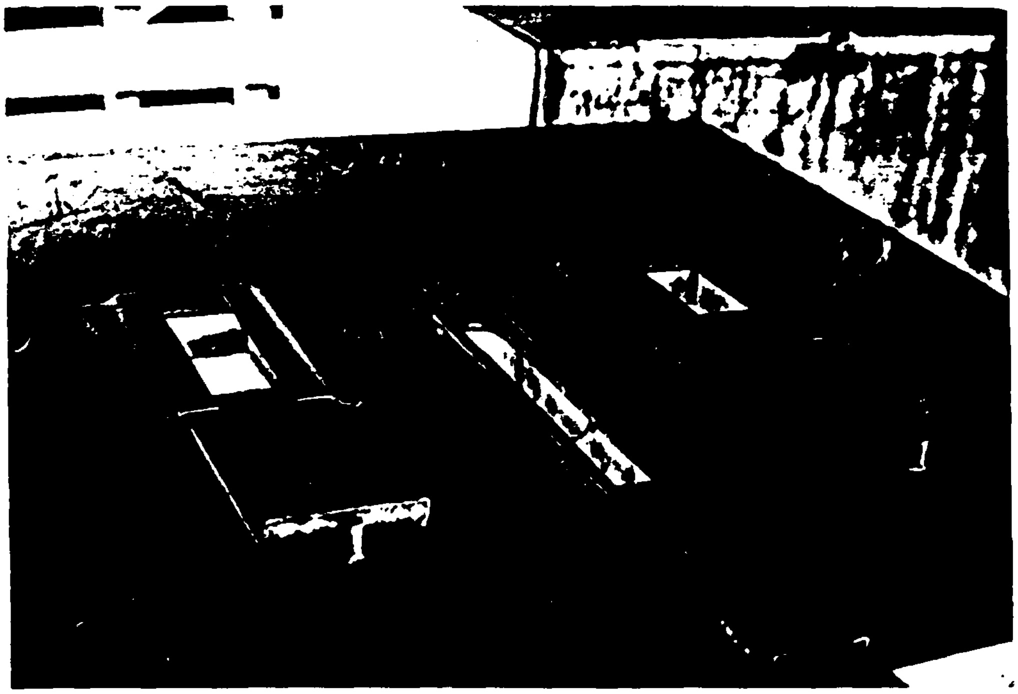
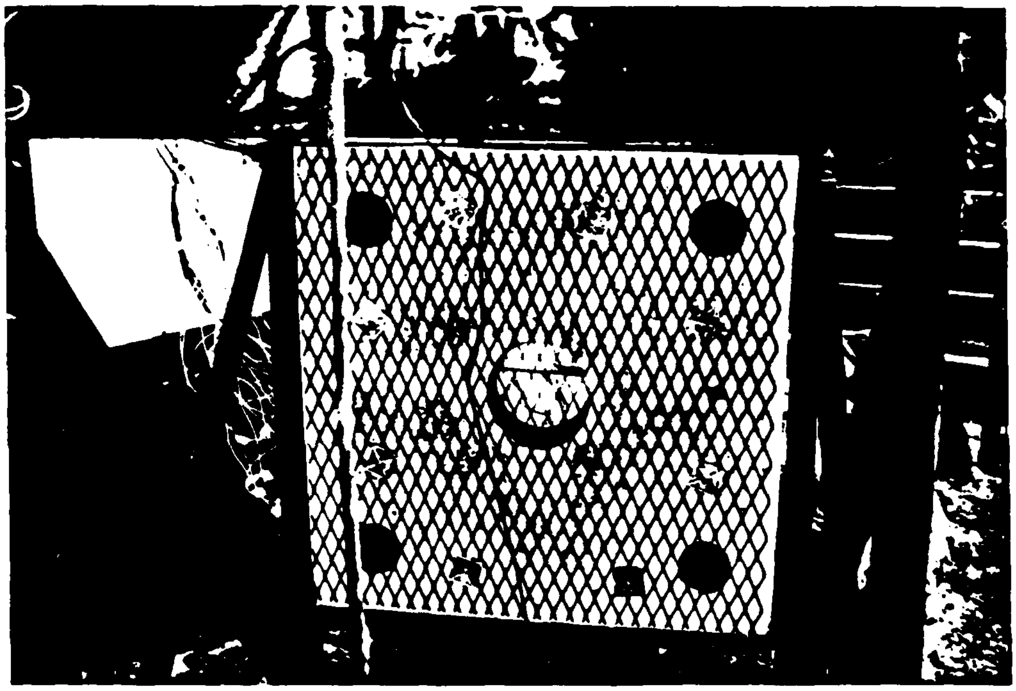


FIGURE 2-1. SMALL-SCALE COAL TEST CHAMBERS



TOP VIEW



BOTTOM VIEW

FIGURE 2-2. SMALL-SCALE TEST CHAMBER SHOWING AIR VENTS

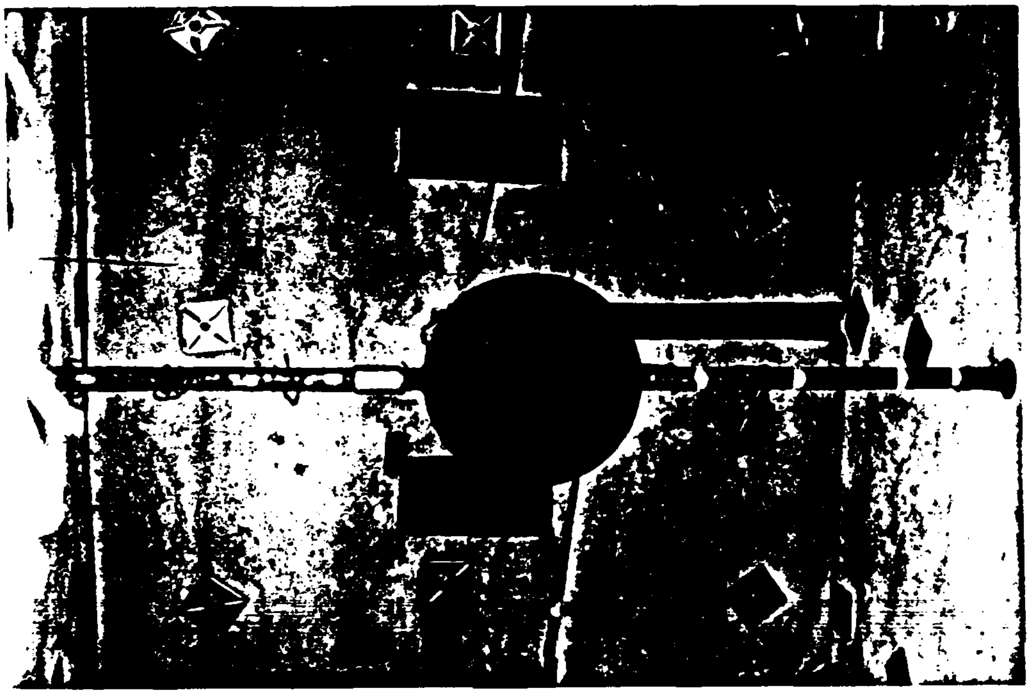
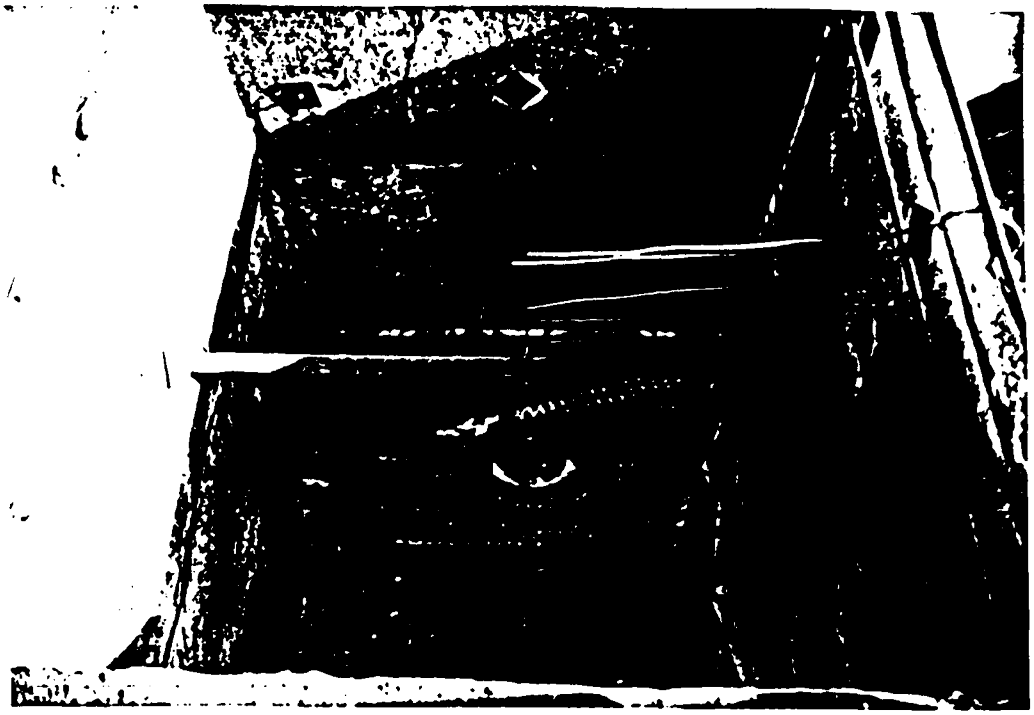
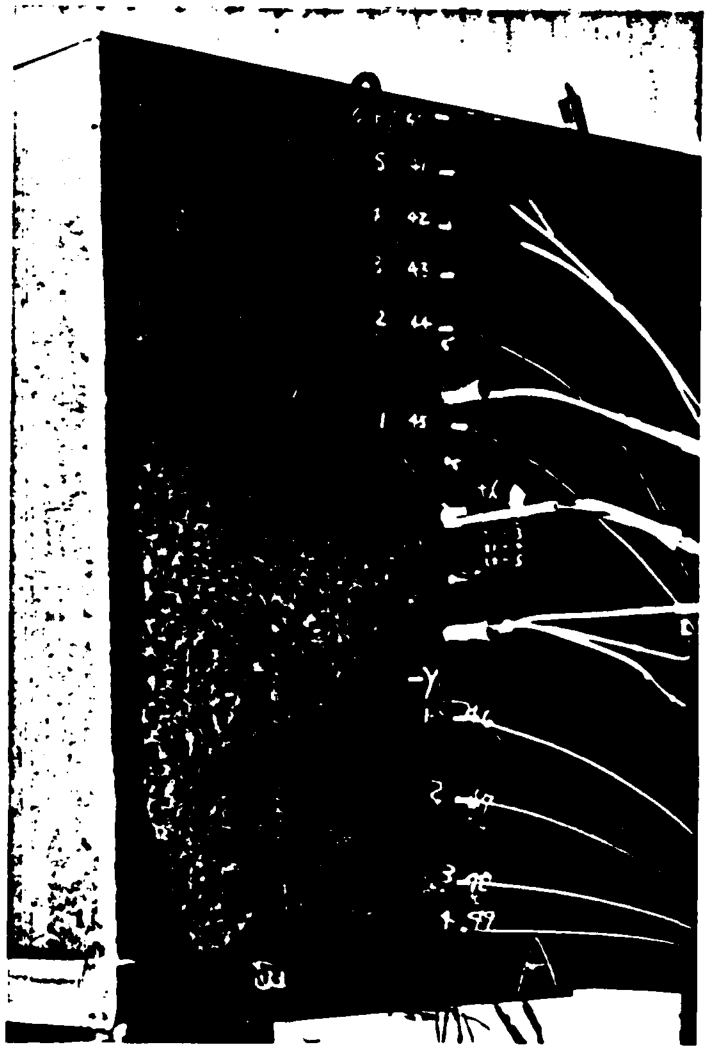


FIGURE 2-3. SMALL-SCALE TEST CHAMBER SHOWING HEATING SPHERE - VIEW FROM BOTTOM OF CHAMBER



INTERIOR



EXTERIOR

FIGURE 2-4. SMALL-SCALE TEST CHAMBER - THERMOCOUPLE PLACEMENT

oxidation of coal. Aboard ship, amounts of methane sufficient to cause an explosion can accumulate rapidly. The lower explosive limit of methane is 5.3 percent by volume in air and the upper explosive limit is 15 percent[11]. Methane levels were monitored to serve as an indicator of combustion as well as a safety measure for personnel in the test area. Carbon monoxide and carbon dioxide are both products of self heating and burning. These gases are often monitored as indicators that combustion is about to take place. The ratio of carbon monoxide to oxygen, the carbon monoxide index, has been found to be an accurate indicator[12]. Gas analyzers were used to continually measure methane, carbon monoxide, carbon dioxide, and oxygen. For Test 1, the gas sample line inlet was located in a void space above the coal. In Tests 2 and 3, an additional gas sample line inset and 4 gas analyzers were placed 2 inches (5.08 cm) below the sphere.

Air velocity was measured using bi-directional velocity probes. There were 4 probes in each chamber, one at the bottom air vent, one in the void space at the top of the chamber, and the remaining two probes were 2 inches (5.08 cm) above and below the sphere.

Smoke is also a product of self heating and combustion. According to Hertzberg[13], smoke is an indicator of combustion in the case of an incipient fire. The spontaneous combustion of coal is a special case of incipient fire. Smoke was monitored to determine the effectiveness of smoke particulates as an indicator of combustion.

Environmental conditions were measured continuously during each test. These included: barometric pressure, humidity, wind intensity, and wind direction. There were four humidity probes in each chamber measuring moisture. A probe was placed at the bottom inlet to the chamber, another in the void space at the top of the chamber. The other probes were placed 2 inches (5.08 cm) above and below the sphere.

Differential pressure was recorded using three differential pressure gauges in each chamber. One gauge measured pressure between the void space at the top of the chamber and the vent at the bottom. The second gauge measured pressure between the bottom vent and 1 inch (2.54 cm) below the sphere. The third gauge measured pressure between the top and bottom of the heat sphere.

Safety was a primary concern in all the spontaneous combustion tests. Alarm systems were installed in the chambers so that if levels of combustible gases were too high, an alarm would sound to warn personnel, and the chamber would be vented. Fire hoses provided backup protection during the tests.

2.2 Spontaneous Ignition Test Procedures

The spontaneous ignition tests were designed to be small-scale simulations of spontaneous combustion of coal in a large hold. The coal was hand loaded into the chamber. One-half inch (1.27 cm) of coal fines were packed around the heat sphere. This accelerated the heating process by preventing heat from escaping. Thermocouples were hand placed as the coal was loaded to ensure correct placement. Figure 2-5 shows this process.

The data acquisition system was started five minutes prior to activating the heat sphere. Air vents on the top and bottom of the chamber were opened to allow natural ventilation through the coal. A heater temperature was selected from the analysis conducted by the Bureau of Mines (see Apendix A.). The heater was then activated. Data was monitored for evidence of thermal runaway, particularly at the time indicated by the Bureau of Mines analysis.

2.3 Data Analysis and Test Results

Six tests were conducted. Each test ran for approximately ten days. In these six tests, there were 31 events consisting of 27 heating events and 4 spontaneous ignitions. For the purposes of this analysis, a "heating event" is defined as an increase in temperature of less than 50°C (122°F) that is sustained over a long period of time. A "spontaneous ignition event," is defined as a temperature increase greater than 50°C (122°F) that occurs very rapidly but is not sustained and falls back to a temperature close to the original.

2.3.1. Spontaneous Ignition Events

Figure 2-6 illustrates the characteristics of a typical spontaneous ignition event. The thermocouple registered 100°C (212°F) at 1210 minutes. It then registered a 200°C (392°F) increase in the next 40 minutes. The temperature returned to about 80°C (176°F) at about 1290 minutes.

If this is a spontaneous ignition and not just an aberration in the thermocouple reading, confirmation should be found in the response of other parameters. When spontaneous ignition occurs there should be a decrease in the available oxygen as the coal burns. Figure 2-7 shows that this did occur. It is interesting to note that prior to the rise in temperature, there is an increase in oxygen followed by a sharp drop. Carbon monoxide and carbon dioxide are by-products of combustion and one sees a slight increase in both (see Figure 2-7) after the temperature spike. Water vapor is also given off as a by-product of combustion. Figure 2-8 shows relative humidity increasing at the outlet after the event. It appears that the increase in oxygen sparked a spontaneous ignition event but that there was insufficient oxygen to sustain the fire.

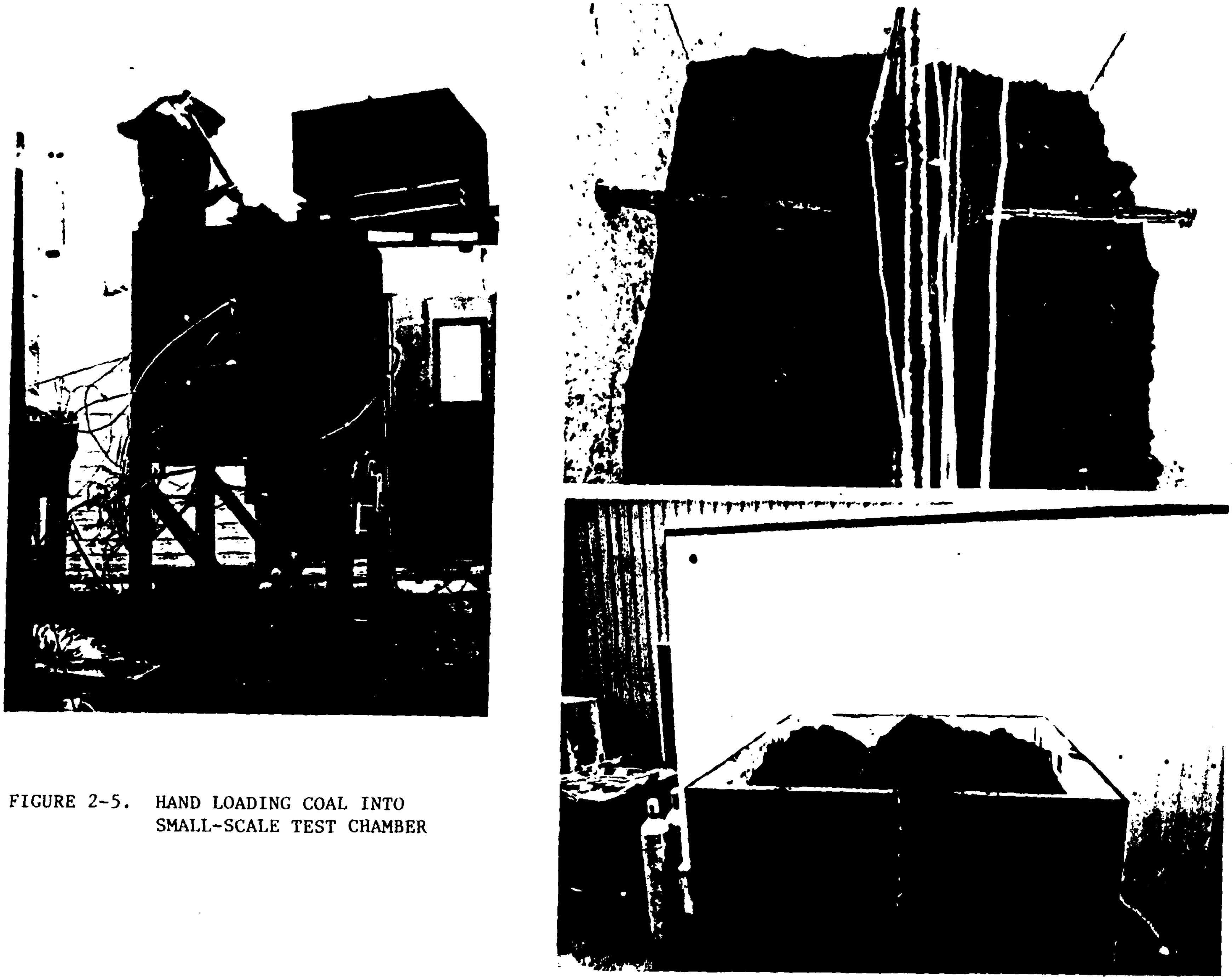


FIGURE 2-5. HAND LOADING COAL INTO SMALL-SCALE TEST CHAMBER

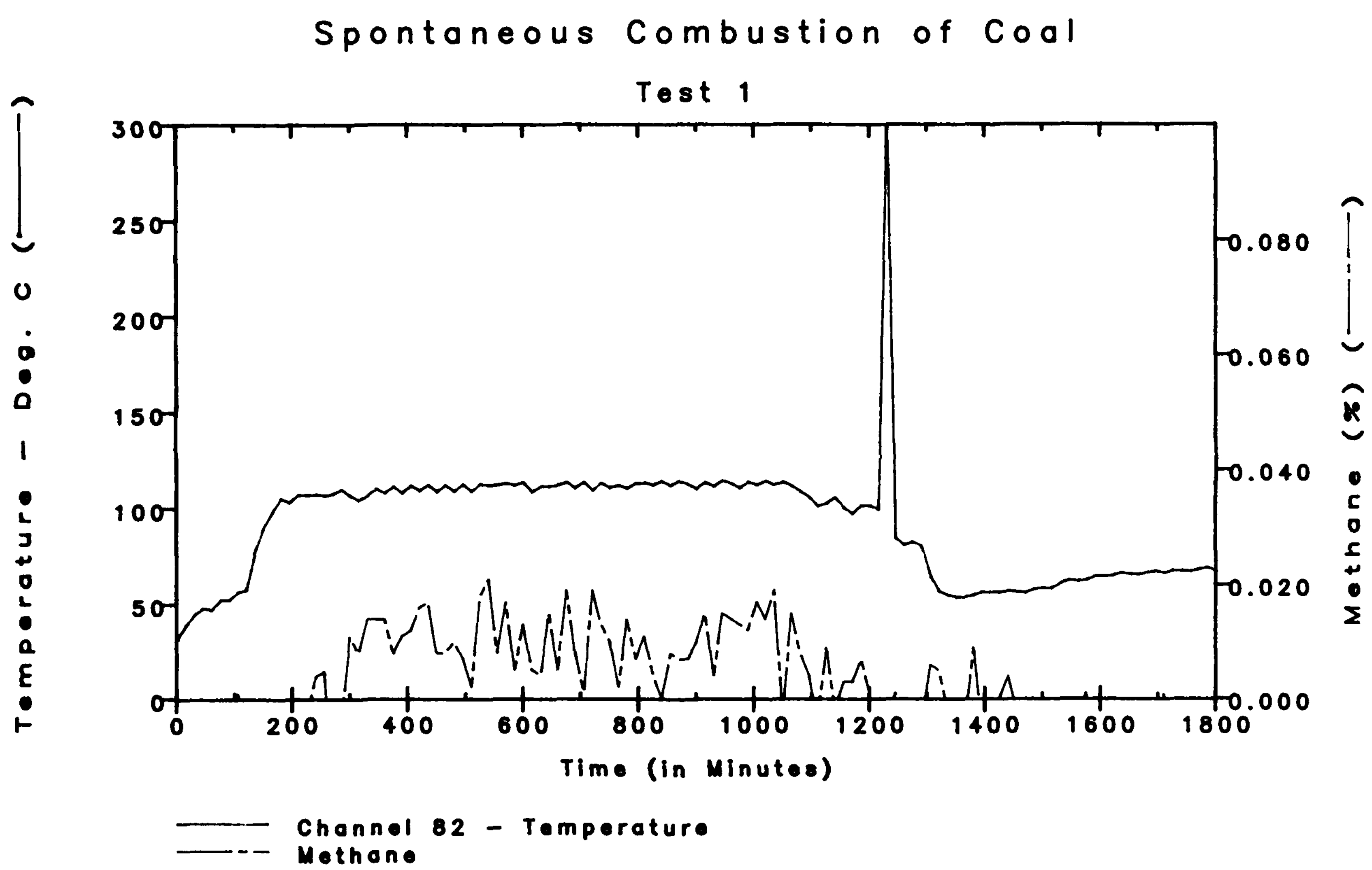


FIGURE 2-6. SPONTANEOUS IGNITION EVENT - TEMPERATURE AND METHANE CONCENTRATION HISTORIES

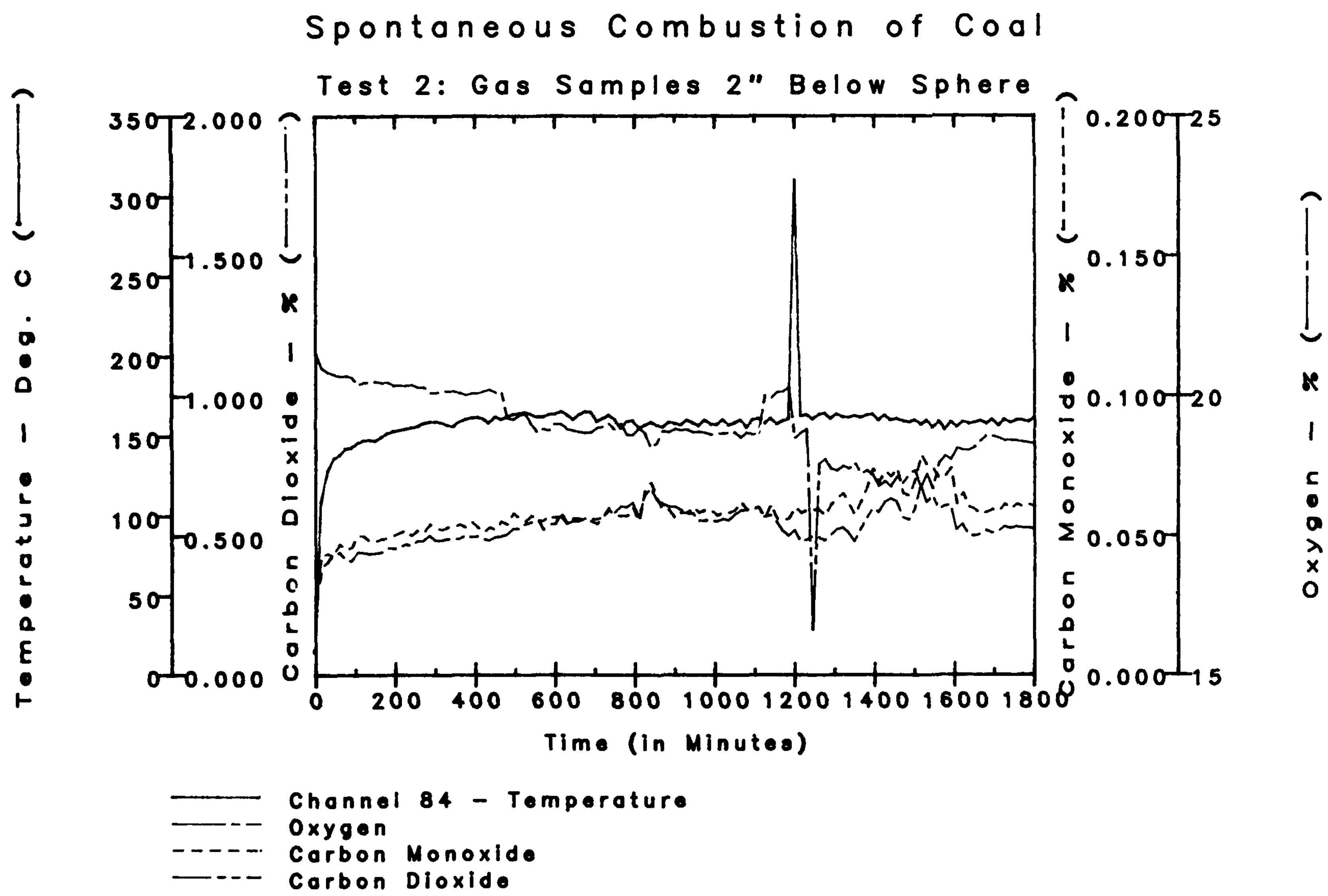


FIGURE 2-7. SPONTANEOUS IGNITION EVENT - GAS CONCENTRATION HISTORIES

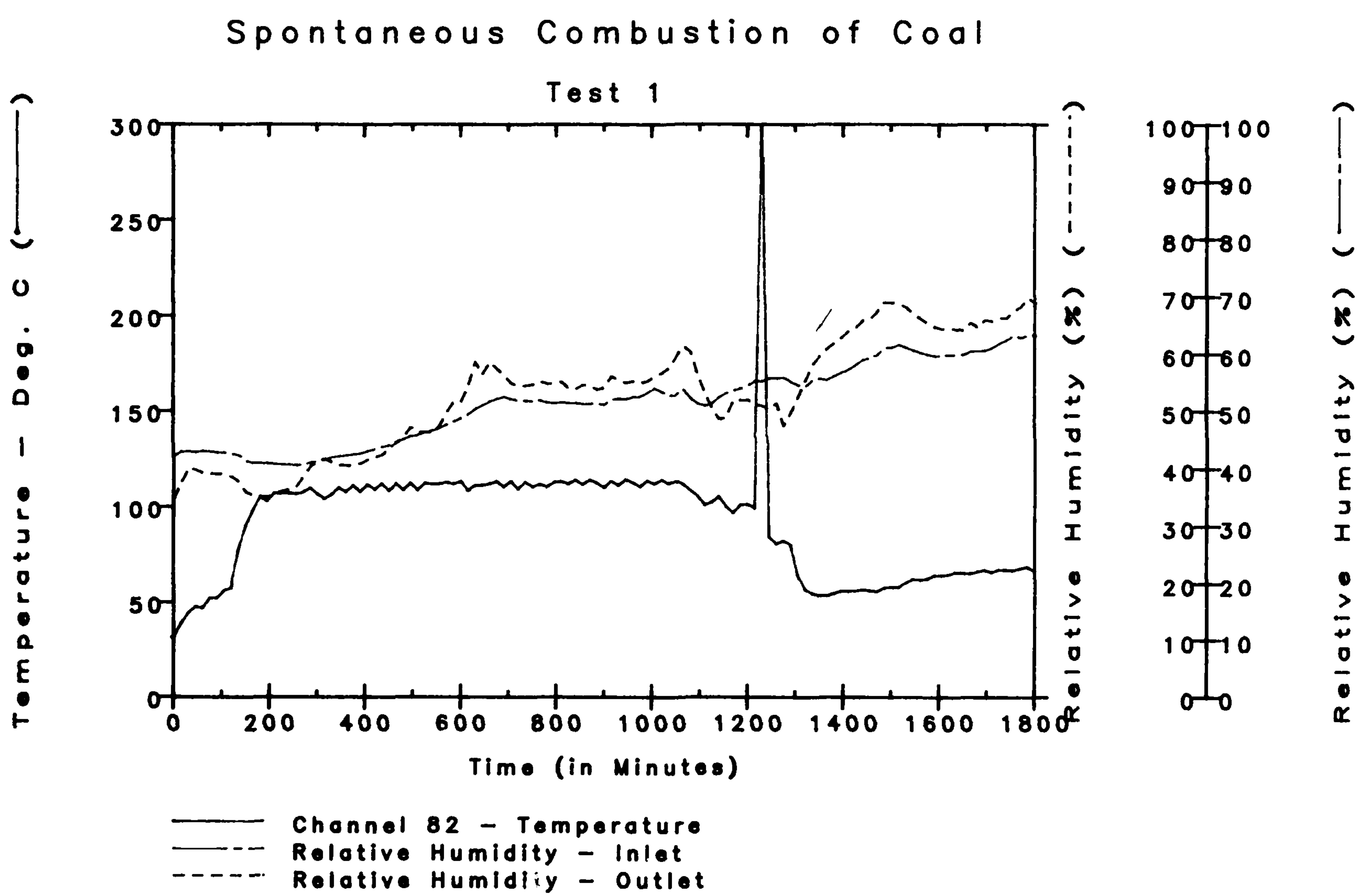


FIGURE 2-8. SPONTANEOUS IGNITION EVENT - HUMIDITY LEVELS

2.3.2 Heating Events

Figure 2-9 illustrates a heating event. The thermocouple registers a temperature of 150°C (302°F) before rising 30°C (86°F) in a short period of time. The temperature remained at this level for about 230 minutes before returning to 150°C (302°F). This event differs from the spontaneous ignition event in several ways. As stated in the definition, the rise in temperature is less and the time at the elevated temperature is long. It should also be noted that the oxygen concentration remains steady while the carbon monoxide and carbon dioxide concentrations decrease slightly during the time of the elevated temperatures and then decrease more rapidly after the temperature has returned to 150°C (302°F). When heated, water vapor will evaporate, lowering relative humidity. Figure 2-10 shows this to be the case. All these factors indicate that combustion was not occurring during the elevated temperature regime.

Most of the heating events occurred along the axis that coincided with the metal rod supporting the heat sphere. It is believed that heat transferred along this rod and caused the temperature rises noted. This is confirmed by viewing other thermocouples along this axis. Figure 2-11 shows that the four thermocouples located along this rod have similar temperature profiles at the same time. It also shows that the greatest amount of heating occurs in the thermocouple closest to the heat sphere with the temperature decreasing along the axis towards the outer edge of the coal pile. However, this was not consistent in all of the heating events.

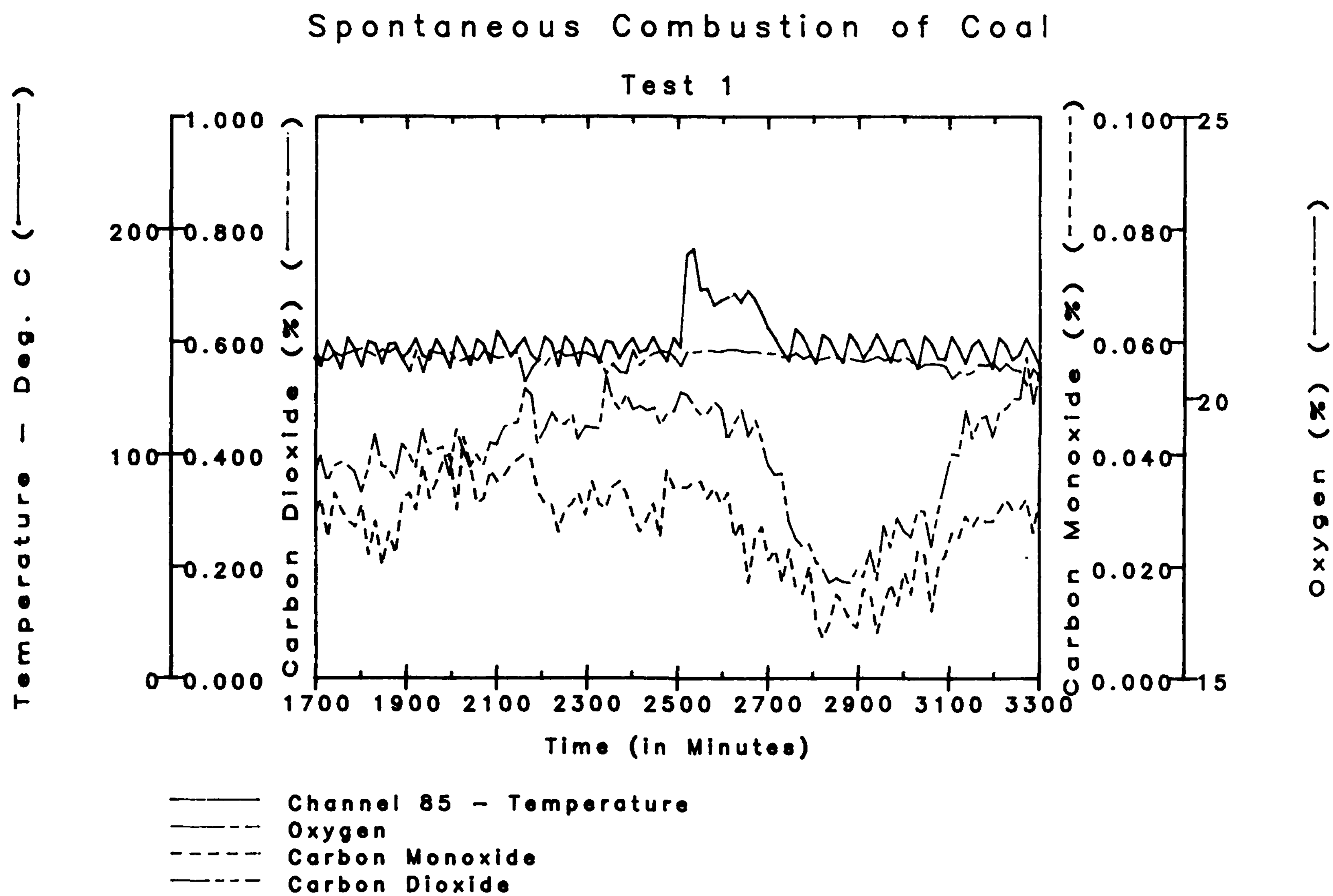


FIGURE 2-9. HEATING EVENT - TEMPERATURE AND GAS CONCENTRATION HISTORIES

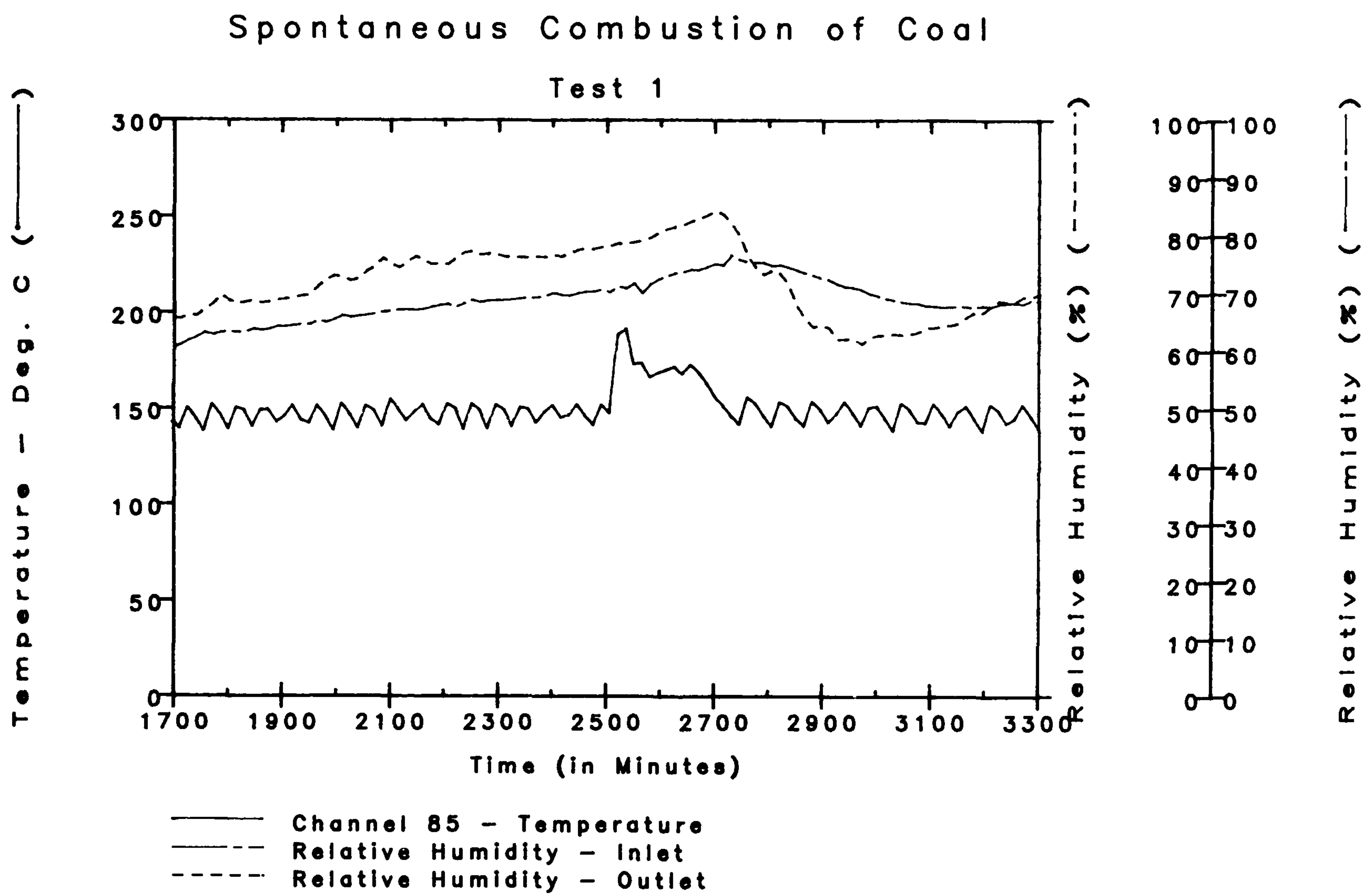


FIGURE 2-10. HEATING EVENT - HUMIDITY LEVELS

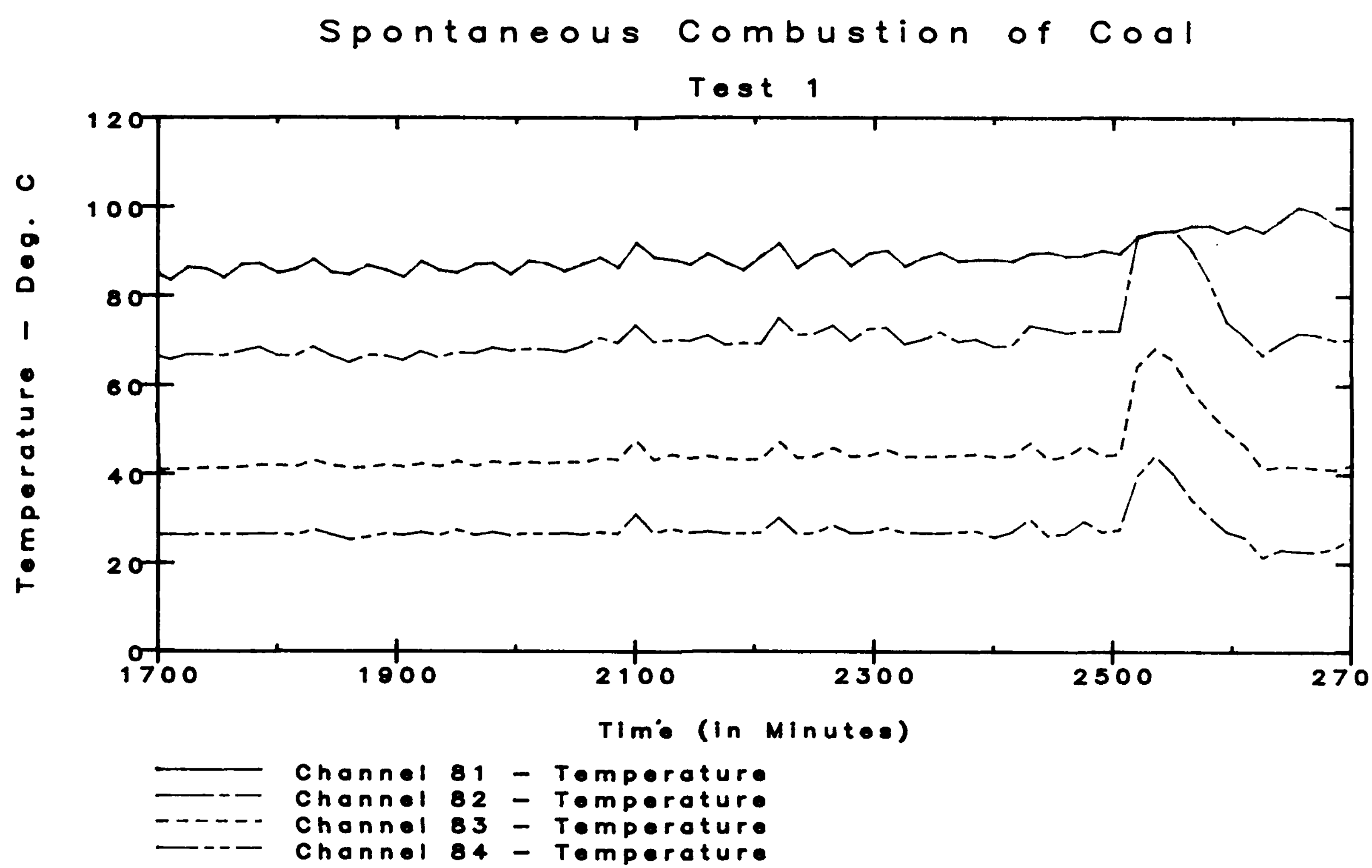


FIGURE 2-11. HEATING EVENT - TEMPERATURE ALONG HEATING SPHERE SUPPORT AXIS

3.0 PERMEATION STUDIES

This study was undertaken to determine the relative rates of permeation of two gases which could be used as fire suppression agents (carbon dioxide and nitrogen) through a coal pile.

3.1 Objectives

The specific objectives of this study were to provide the following information:

(1) The effectiveness of carbon dioxide and nitrogen in displacing oxygen and other coal gases (e.g., methane) present within a coal pile.

(2) 3 The rate at which oxygen concentrations returned to normal levels within a coal pile after injections of carbon dioxide or nitrogen.

(3) The effect of the following on the movement of oxygen, carbon dioxide, and nitrogen gases within a coal pile:

(a) carbon dioxide and nitrogen discharge rates
(b) Natural convection and buoyancy effects
(c) Presence of a heat source within a coal pile

3.2 Laboratory Studies

In order to acquire the necessary data to provide this information, a series of tests were conducted under controlled conditions at the Research and Development Center laboratories in Groton, CT and on-board the test vessel M/V MAYO LYKES in Mobile, Alabama. The laboratory studies were designed to evaluate the sampling mechanism and analytical detection system for use in subsequent larger scale field testing. The sampling probe used in these tests is basically a three point sampling device housed in two concentric cylindrical tubes. Each sampling point is a chamber sealed from the other chambers to prevent gas movement. Each chamber of the inside tube is equipped with a gas sampling tube (1/4" O.D.(.984 mm) stainless steel, and a thermocouple). The center chamber of each probe was also equipped with a temperature sensor, a dew point hygrometer, and a differential pressure sensor.

The gas sampling lines were terminated at a 4-way switching valve, having a common port. One position was permanently sealed to serve as a shut-off between sampling times, with the common port being used to draw samples from any of the three chambers, A, B, or C. Gas samples were drawn using 50 milliliter gas sampling syringes from the common port which was terminated with a septum to maintain a closed gas tight system.

All gas samples were analyzed by gas chromatographic techniques employing a prototype UV detector coupled to the gas chromatograph. All analyses were performed using a carbosieve column.

In the initial laboratory studies, one sampling probe was installed at the midpoint of a 55-gallon drum. Coal was then loaded into the drum by hand. Only the B, or center, chamber of the probe, which was located at the drum's midpoint, was monitored. Carbon dioxide or nitrogen was injected into the bottom of the drum containing the coal. The injections were made at controlled discharge rates of 2 and 4 liters per minute. Discharge times for each gas were one hour.

Figures 3-1 and 3-2 each summarize the results of tests at low and high discharge rates, respectively. The initial injection was made at time zero on these figures. As can be seen, both gases, carbon dioxide and nitrogen, were effective in displacing both the oxygen and methane gases present in the coal piles. Methane could be more fully displaced than oxygen. Prior to oxygen depletion within this drum of coal, the oxygen level was observed to increase slightly, indicating that the oxygen present at the bottom of the drum was probably being forced upward through the coal pile. This slight increase, occurring 2 minutes after the discharge of either gas, can best be explained as back pressure existing within the coal pile caused by both low porosity and permeation characteristics of the coal pile. The type of coal used in this study was very friable and easily crumbled into fines. The composition of the coal within the drum during these tests was estimated to be 60 percent the size of sand and smaller sized particles, and 40 percent chunks ranging from 1/2-inch (1.27 cm) to greater than 3-inch (7.62 cm) pieces. Although porosity and permeation measurements were not made, it can be assumed that the porosity and permeation values for this type of composition would range from 20-35 percent and 30-80 percent, respectively.

After twenty-four hours, the coal drum gas composition, i.e., oxygen and methane concentrations were essentially back to their original values as seen in Figures 3-1 and 3-2. These tests were repeated 10 times with the same observations being made each time.

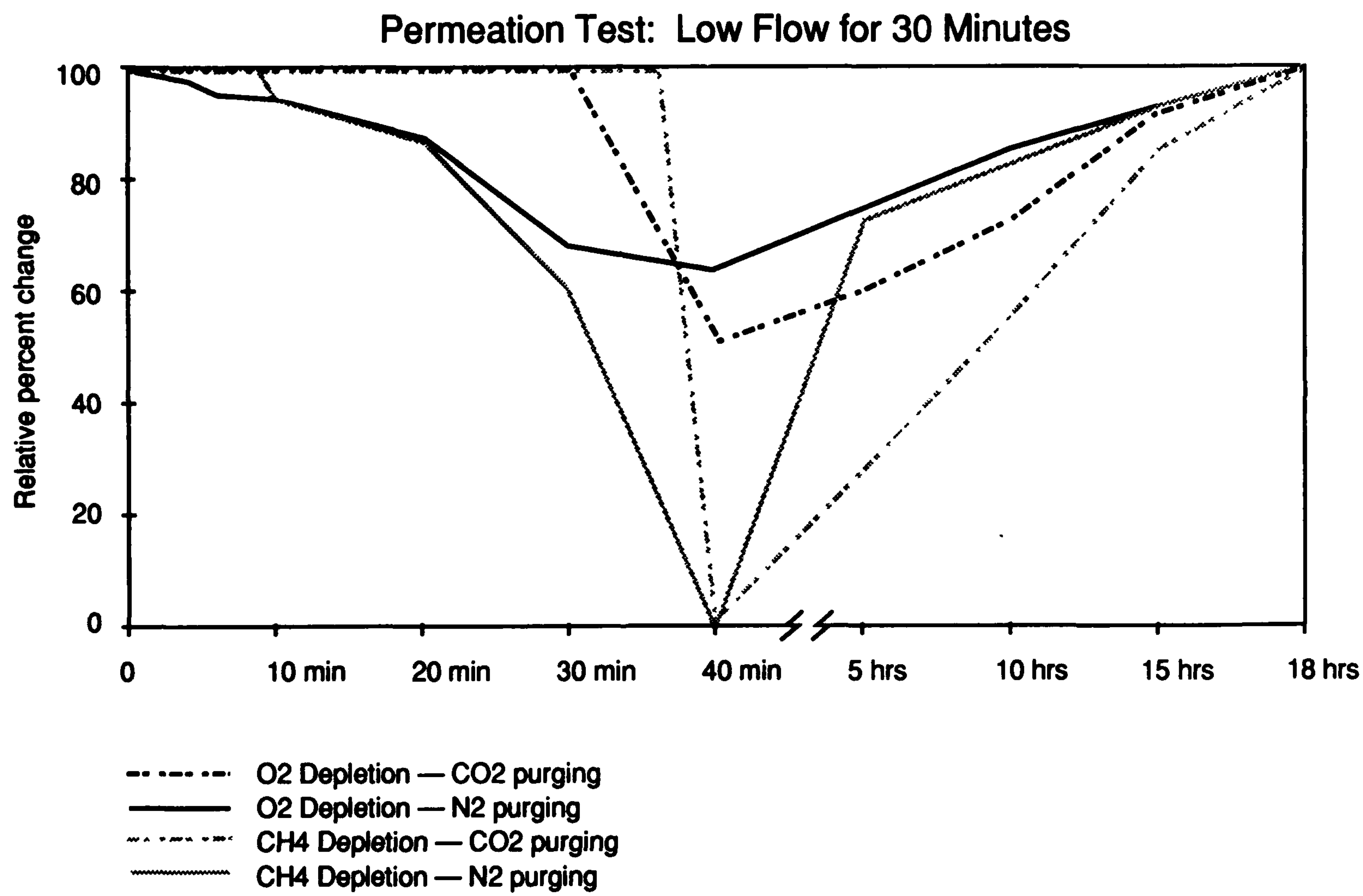


FIGURE 3-1. OXYGEN AND METHANE DISPLACEMENT BY LOW FLOW RATE INJECTION OF CARBON DIOXIDE OR NITROGEN

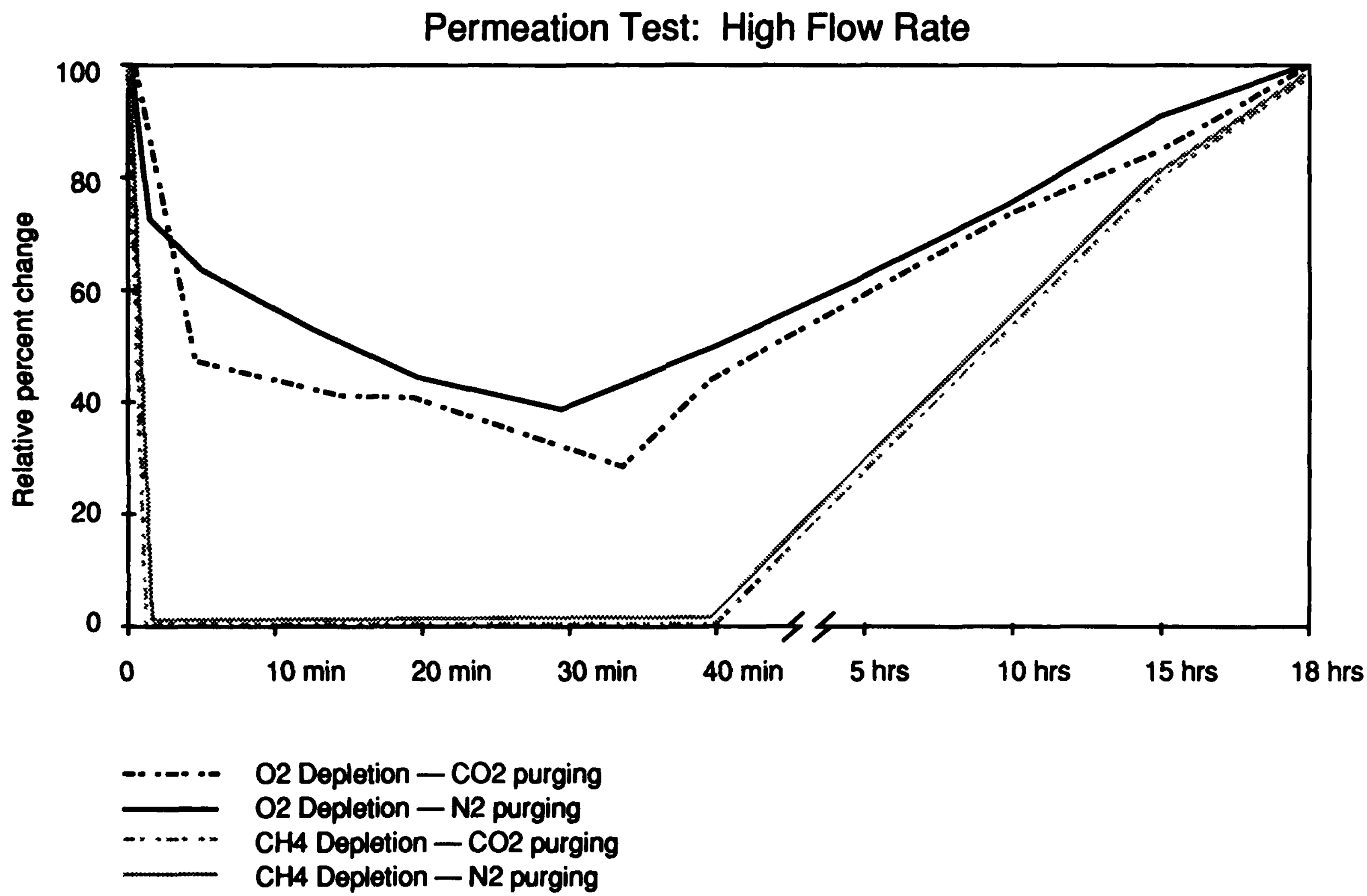


FIGURE 3-2. OXYGEN AND METHANE DISPLACEMENT BY HIGH FLOW RATE INJECTION OF CARBON DIOXIDE OR NITROGEN

3.3 Large Scale Field Testing

A detailed test plan was drawn up for testing a large scale coal pile, 3 x 3 x 25 feet (9.14 x 9.14 x 76.2 meters), on board the test vessel M/V MAYO LYKES at the Fire and Safety Test Detachment in Mobile, Alabama. The plan was based on the laboratory studies. It was designed around the ability to detect both low level oxygen and methane concentrations. Figure 3-3 shows the coal pile configuration, the vertical chamber, and the instrumentation which was used during all field tests. This test chamber was an existing escape trunk aboard the test vessel. All openings were sealed. The inside configuration was not uniform from top to bottom. The existing ladder within the escape trunk was removed, however, at each level a "step" area was left which was previously used by personnel to enter the trunk to ascend or descend the trunk ladder. Loading of the coal was accomplished by hand and shovel. The coal loading sequence was as follows:

(1) Coal was "hand packed" around the bottom gas discharge point, and around three (3) fog nozzles to insure proper upward orientation of the fog nozzles.

(2) Coal was then loaded by shovel up to the first gas sampling probe level and the gas sampling probe was installed.

These two processes were repeated until the entire trunk had been filled. As in the case with the bottom discharge nozzles, coal was hand packed around the midpoint discharge nozzles to insure proper upward orientation.

3.4 Data Analysis and Test Results

The test plan was designed around the use of both oxygen and methane concentrations to determine when the coal pile gas composition had returned to essentially its original concentration before starting the next test. Methane concentration levels were also used to determine the effectiveness and rate at which carbon dioxide and nitrogen would permeate through the void space within the coal pile. When coal is wet, no significant amount of methane is being released from the coal and thus the concentration of methane in the coal pile is minimized. A period of 4 months had elapsed between the time laboratory studies were conducted and the large scale coal pile testing started. The coal used had been stored outside and "repacked" once when it was suspected that spontaneous combustion was occurring within the coal pile. Thus the coal for the large scale tests had a higher moisture content than that used in the laboratory studies.

Analysis of background gases present in the coal contained within the escape trunk of the test vessel revealed that no significant levels of methane were present within the coal pile. Physical examination of the coal pile revealed that

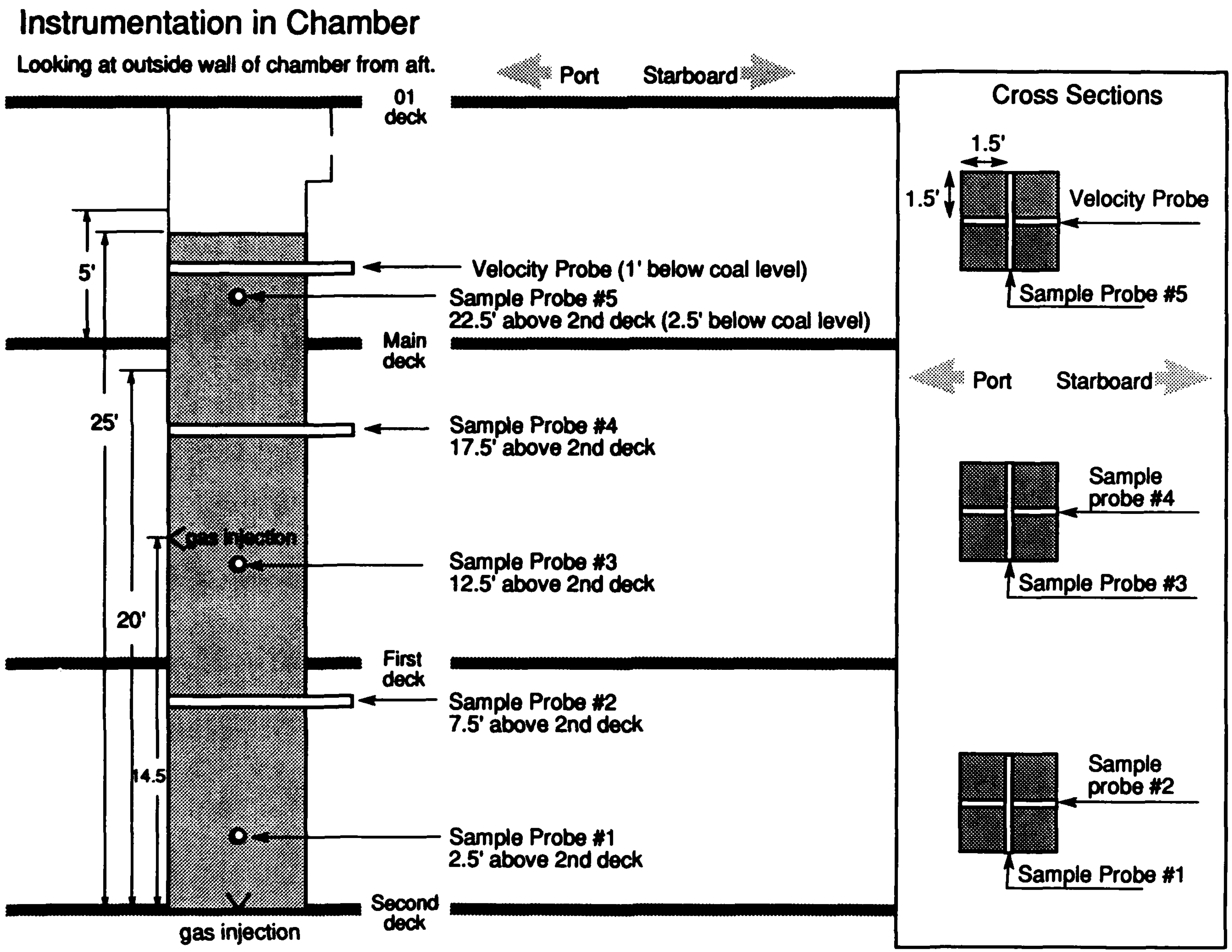


FIGURE 2-3 LARGE SCALE PERMEATION TEST ARRANGEMENT

it was wet. This was further substantiated during the "heat ball" testing sequence in which live steam was emitted from the coal pile as the heat ball temperature rose above 100°C (212°F). This fact prevented the use of methane concentrations as a supporting measurement in the effectiveness of carbon dioxide or nitrogen to displace existing gases within the coal pile for the duration of the field study.

The first two tests involved the release of carbon dioxide and nitrogen at identical discharge pressures of 40 psi, (275.8 kPa) and low flow rates (40 cubic feet (1.13 cubic meters) per hour) from the bottom of the coal pile. Based on the physical characteristics of the coal used in this study, i.e., being extremely friable and easily broken into fine particles, a worst case porosity of 35 percent would result in approximately 80 cubic feet (2.26 cubic meters) of coal gas being present in this pile. No porosity calculations were made since the physical nature of the coal and the manner in which the trunk was filled resulted in a heterogenous configuration. Assuming a 35 percent porosity and an acceptable permeation factor of 30 after a one-hour discharge of gas at 40 cubic feet (1.13 cubic meters) per hour at least 1/3 of the gas volume in the coal pile should be replaced. Therefore, it was anticipated that changes in the oxygen levels would be detected at level 1 and possibly at level 2 (the lowest sampling levels, refer to Figure 3-3). Analysis of the samples collected after these first two tests (low flow discharges of carbon dioxide and nitrogen) revealed no significant changes in oxygen concentrations were detected at level 1. Based on the results obtained from the initial two tests, it was decided that all future testing would be conducted at 50 psi (344.7 kPa) and a low injection flow rate of 50 cubic feet (1.42 cubic meters) per hour or a high injection flow rate of 150 cubic feet (4.25 cubic meters) per hour.

As the testing sequence proceeded, an additional factor was discovered which explains the ineffectiveness of either carbon dioxide or nitrogen in depleting oxygen concentrations at level 1 during these first two tests. The base plate sealing the bottom of the trunk was not air tight. Discharged gases, particularly carbon dioxide, were detected leaking through the bottom plate during later tests involving the discharge of carbon dioxide from the bottom.

During the test sequence, particularly after test No. 15, it was observed that the oxygen concentrations after air purging were not constant from test to test and, in some cases, showed extreme variations from level to level. Figure 3-4 shows the initial oxygen concentration for the B chamber of each level for the duration of the test sequence. Therefore, any conclusions drawn from the test data presented in the next section are

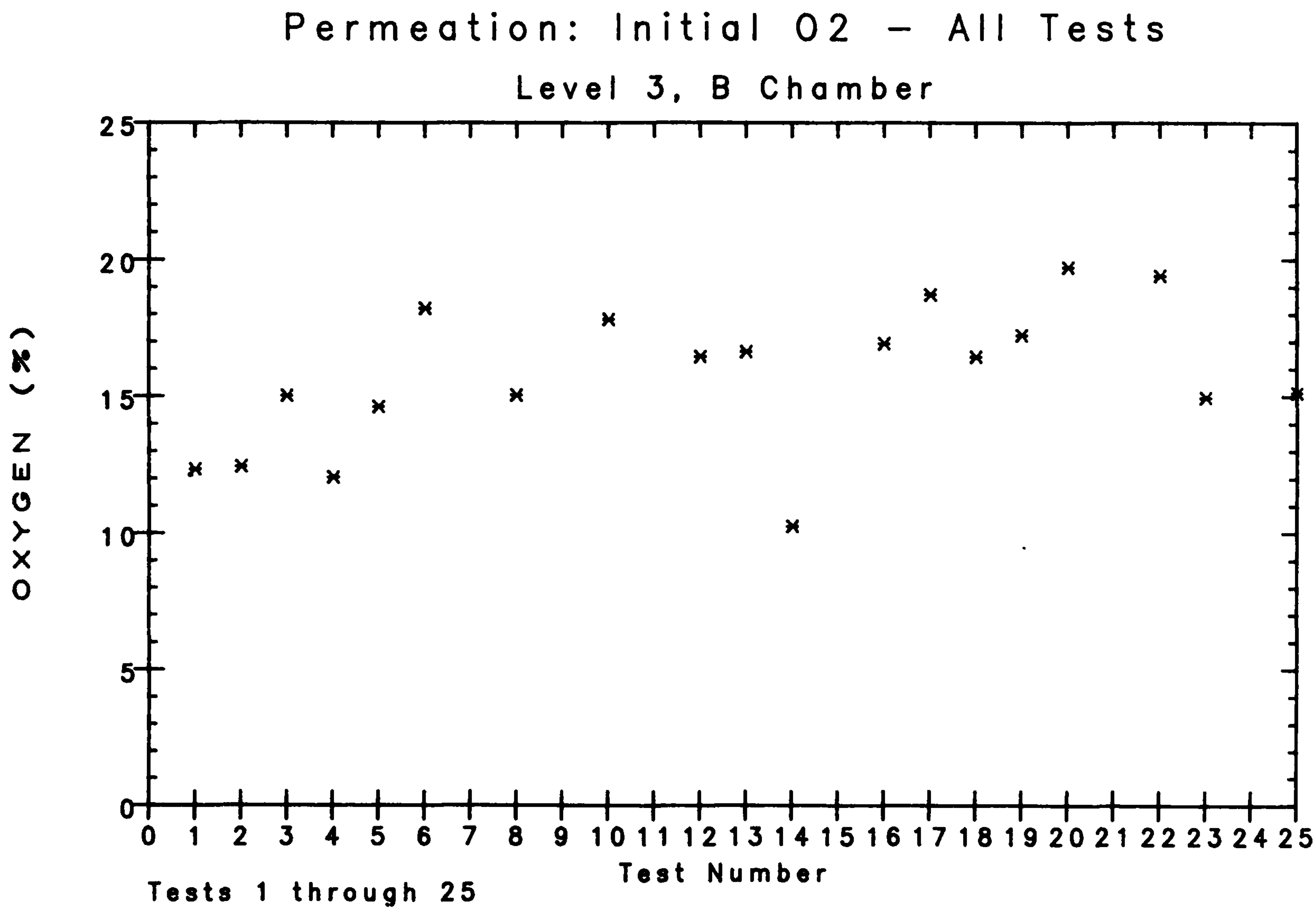


FIGURE 3-4. LARGE SCALE PERMEATION TEST - INITIAL OXYGEN CONCENTRATIONS - ALL TESTS

relative to the existing oxygen concentrations at each level at the start of each test.

The results and conclusions drawn from large-scale field testing on the 3 x 3 x 25 foot (3.14 x 3.14 x 76.2 meter) coal pile are presented below by comparing the effects and behavior of carbon dioxide and nitrogen under identical discharge conditions. These discussions will be restricted to observations made at only the B or center chamber of each probe since the A and D chambers were subject to wall effects.

3.4.1. <u>High Flow - Bottom Injection</u>

Figures 3-5 and 3-6 show the changes in oxygen concentrations during and after the discharge of carbon dioxide and nitrogen respectively. In each case the gas was continuously discharged for 60 minutes at a constant flow rate of 150 cubic feet (4.25 cubic meters) per hour at 50 psi (344.7 kPa). The discharge was made from a three point source at this level. By comparing these two figures, it is obvious that nitrogen has a greater effect on the oxygen concentrations than does carbon dioxide. Nitrogen has a greater effect in the depleting of oxygen concentrations at levels 1, 2 and 3 than does carbon dioxide. The effectiveness of nitrogen is even more apparent when comparing the oxygen concentrations at levels 1, 2 and 3, 60 minutes after the gas discharge was stopped (i.e., at 120 minutes on the figures). The oxygen concentration at level 1 (the closest chamber to the discharge point) increased significantly 60 minutes after the discharge of carbon dioxide ended, whereas the oxygen concentrations at levels 2 and 3 were still depleted 60 minutes after the nitrogen discharge was stopped.

These test results are consistent with the respective gas densities for carbon dioxide and nitrogen, 1.977 grams/liter and 1.251 grams/liter, respectively. The rapid increase in oxygen concentration at level 1, 60 minutes after the carbon dioxide discharge ended, is a direct result of the bottom of the trunk not being air tight and carbon dioxide sinking due to its density and escaping through the trunk bottom plate. The density of nitrogen is slightly less than air (1.293 grams/liter) and would be expected to move upwards slowly through the coal pile and deplete oxygen concentrations at higher levels. The rate of this nitrogen movement is a function of coal pile permeation and gas diffusion rates.

Interestingly, the oxygen concentration at level 2 was observed to increase slightly 20 minutes after the discharge of nitrogen started. This phenomenon was also detected in the small-scale laboratory testing. A possible explanation for this increase is that the coal gas composition at the bottom of the pile is being pushed up at a faster rate than can be passed through the pile based on the pile's low permeation factor.

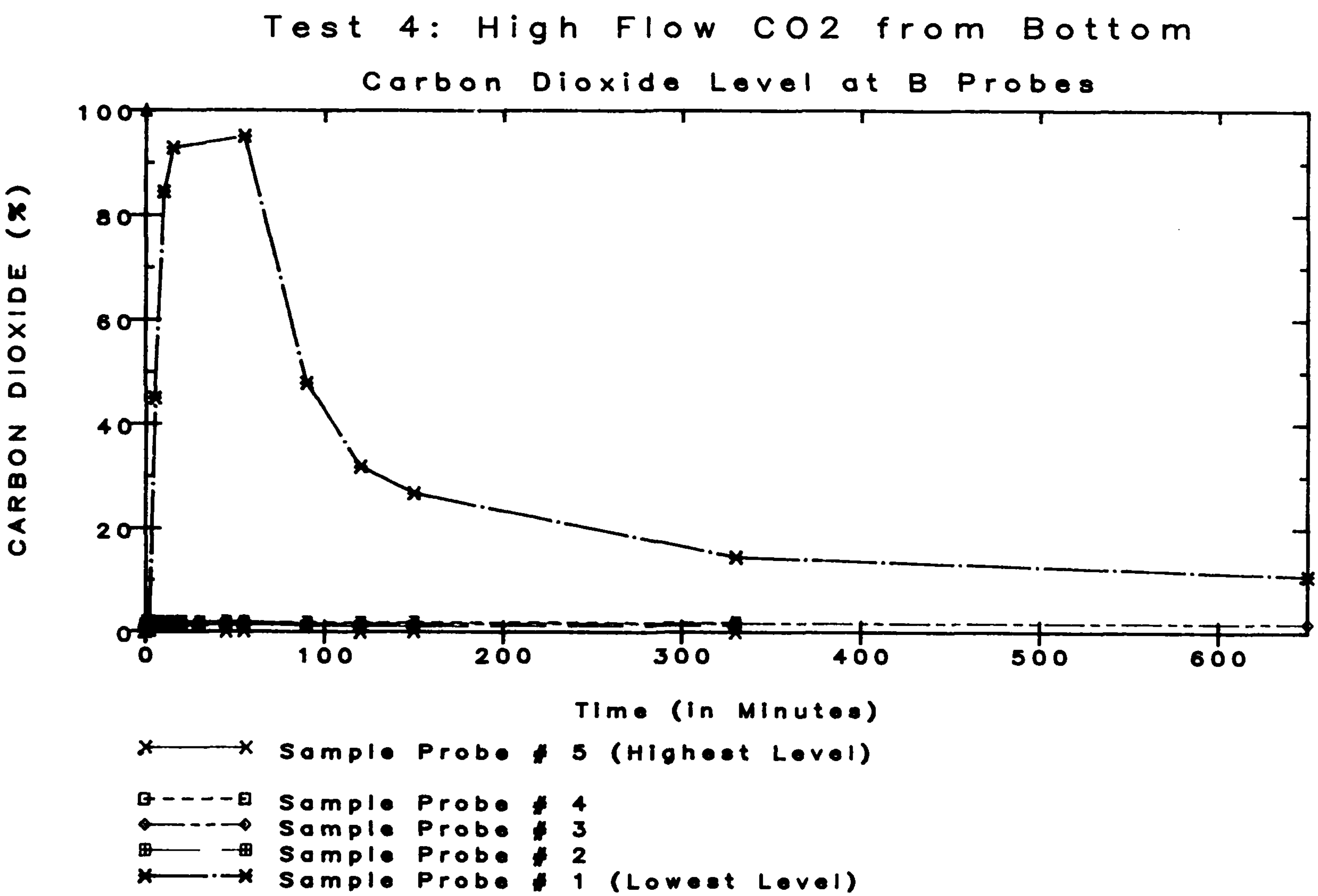


FIGURE 3-5. LARGE SCALE PERMEATION TEST - HIGH FLOW CARBON DIOXIDE INJECTION FROM BOTTOM

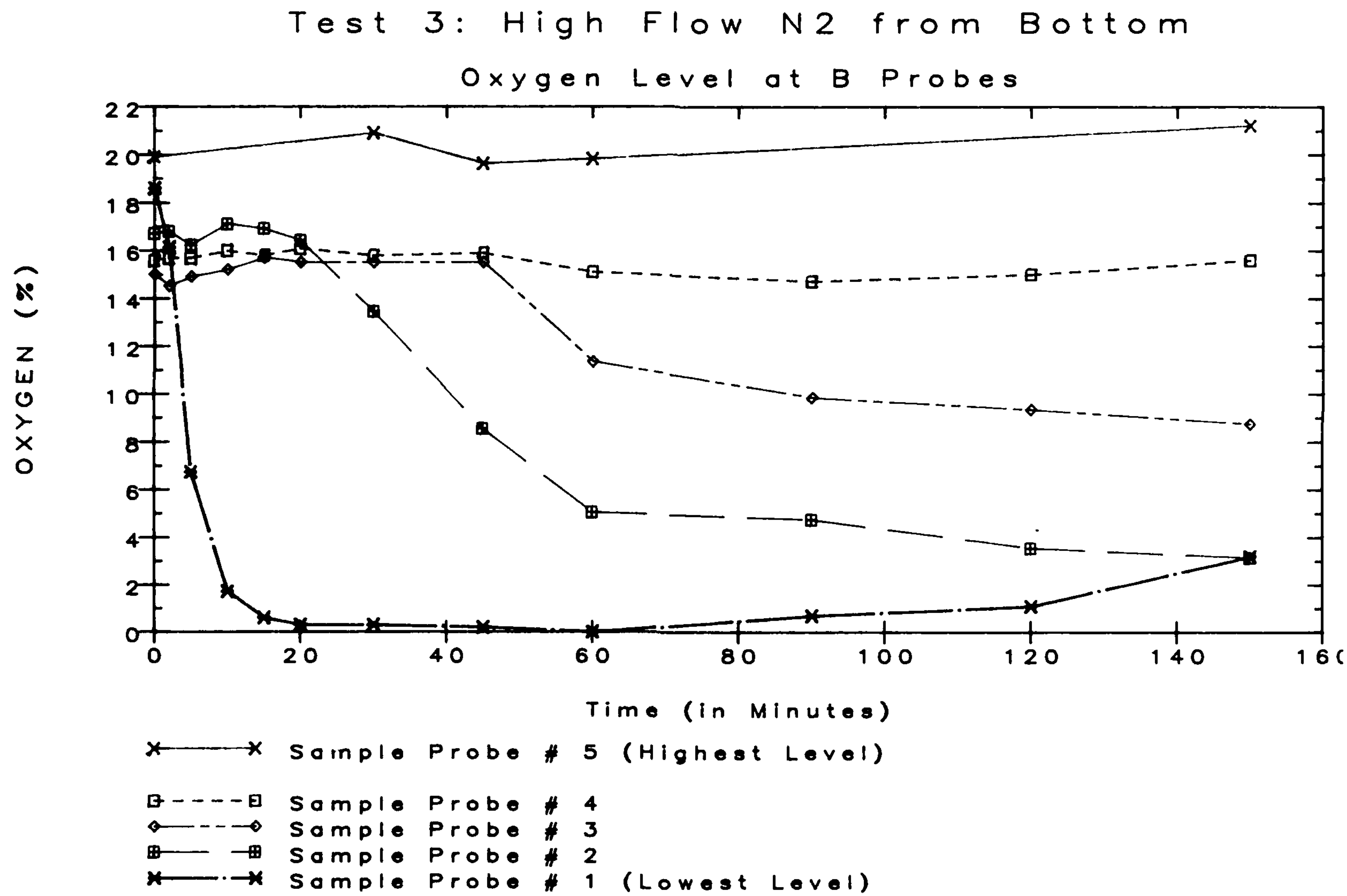


FIGURE 3-6. LARGE SCALE PERMEATION TEST - HIGH FLOW NITROGEN INJECTION FROM BOTTOM

3.4.2. High Flow - Mid-Point Injection

Test results for carbon dioxide and nitrogen discharged for 60 minutes at high flow rates from the mid-point in the coal pile are shown in Figures 3-7 and 3-8. The discharge was made from a three point source at this level. It is apparent that the same conclusions drawn from the comparison on the effects of carbon dioxide and nitrogen in depleting and maintaining depressed oxygen levels within the coal pile from the previous bottom discharge test results can be reached. These conclusions are as follows:

a. carbon dioxide settles through the coal pile. The reason for this settling is due to the greater gas density of carbon dioxide 1.977 grams/liter as compared to nitrogen 1.251 grams/liter. During the discharge of these two gases, the discharge gas temperature of carbon dioxide is significantly lower than that for nitrogen. This lower discharge temperature for carbon dioxide increases the density of carbon dioxide and, therefore, has a greater effect on the rate at which carbon dioxide settles out or moves downward.

b. nitrogen rises based on its lower gas density relative to the existing coal gas density (1.293 grams/liter) which in these tests is assumed to be equivalent to air as a result of large volume air purging from the bottom injection ports between each test. It is obvious that the "coal gas" density existing within this pile during these tests is greater than pure dry air due to its moisture content.

c. oxygen concentrations remain depleted for a significantly longer period of time within the coal pile after the discharge of nitrogen ended relative to carbon dioxide.

d. The rate at which nitrogen moves through the coal pile is significantly faster than that for carbon dioxide. This is undoubtedly the effect of the nearly equal buoyancy between air and nitrogen.

3.4.3. High Flow - Top Injection

In this test sequence, carbon dioxide and nitrogen were discharged from a single point source at the top of the coal pile. The duration of discharge for these tests was 30 minutes rather than 60 minutes used in the previously discussed bottom and mid-point discharges. Test data for these two sequences of tests are shown in Figures 3-9 and 3-10.

It is obvious in viewing this data that similar conclusions can be drawn as were drawn from the tests involving bottom and mid-point discharges. The density of carbon dioxide causes carbon dioxide to sink and the relative neutral

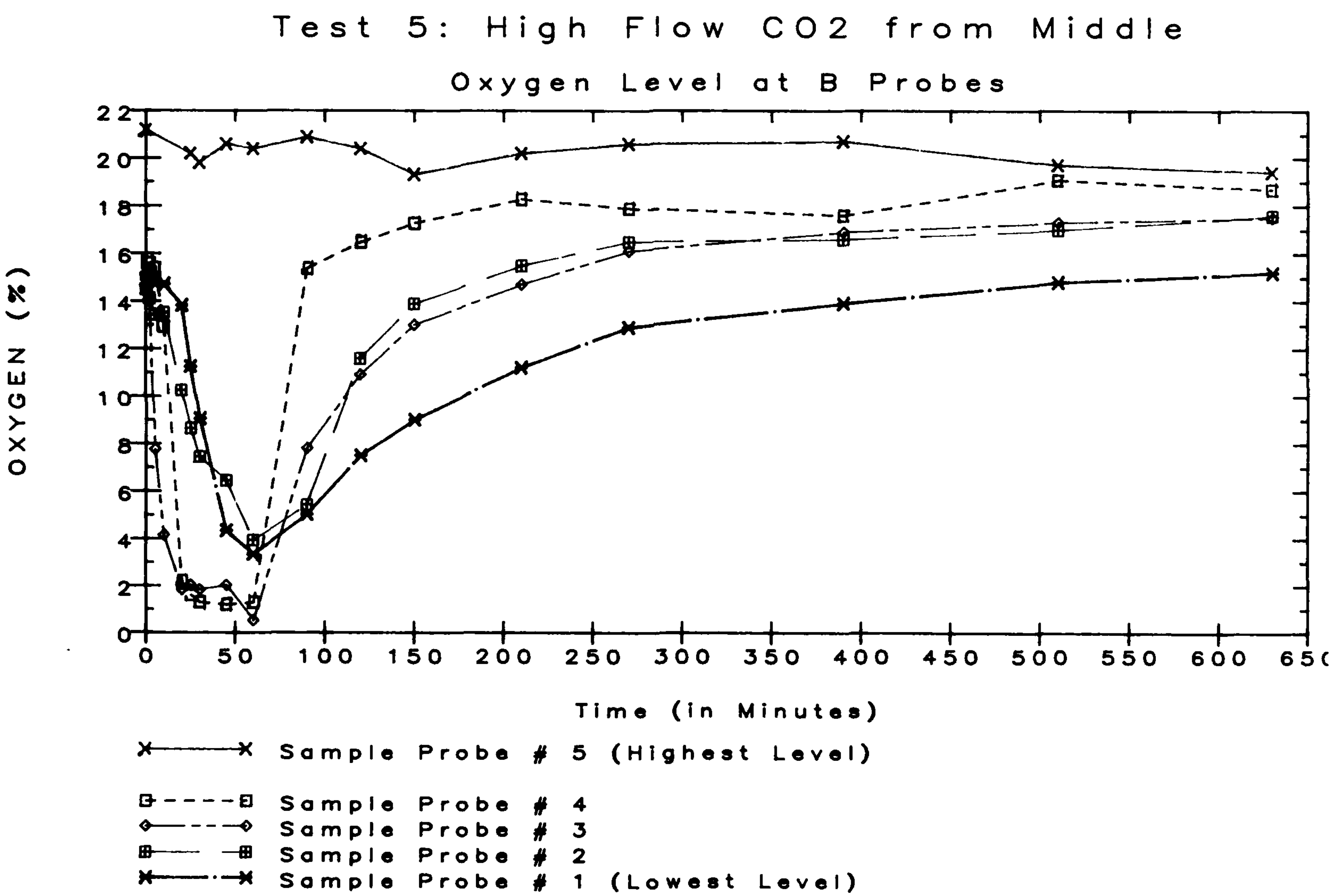


FIGURE 3-7. LARGE SCALE PERMEATION TEST - HIGH FLOW CARBON DIOXIDE INJECTION FROM MID-POINT

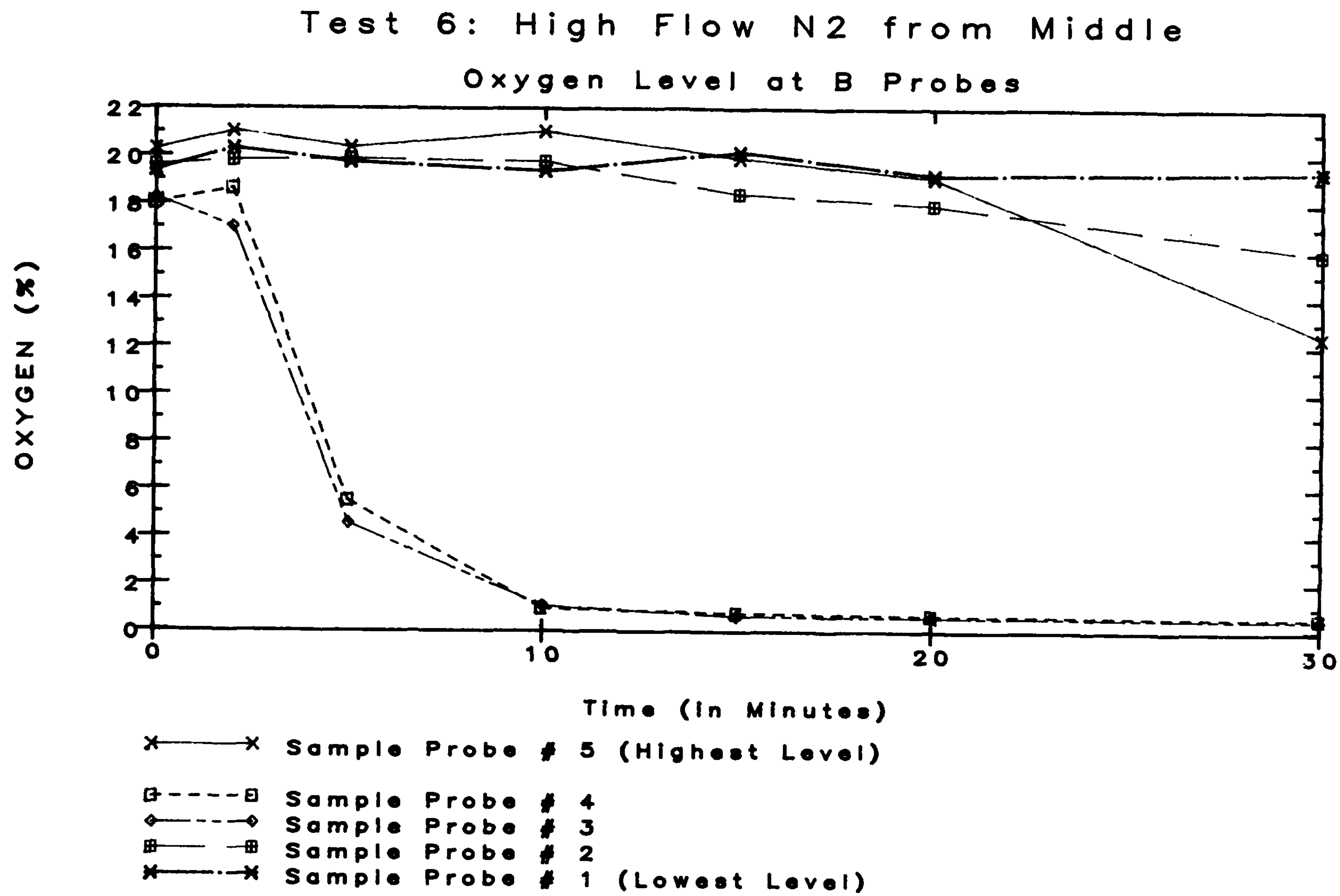


FIGURE 3-8. LARGE SCALE PERMEATION TEST - HIGH FLOW NITROGEN INJECTION FROM MID-POINT

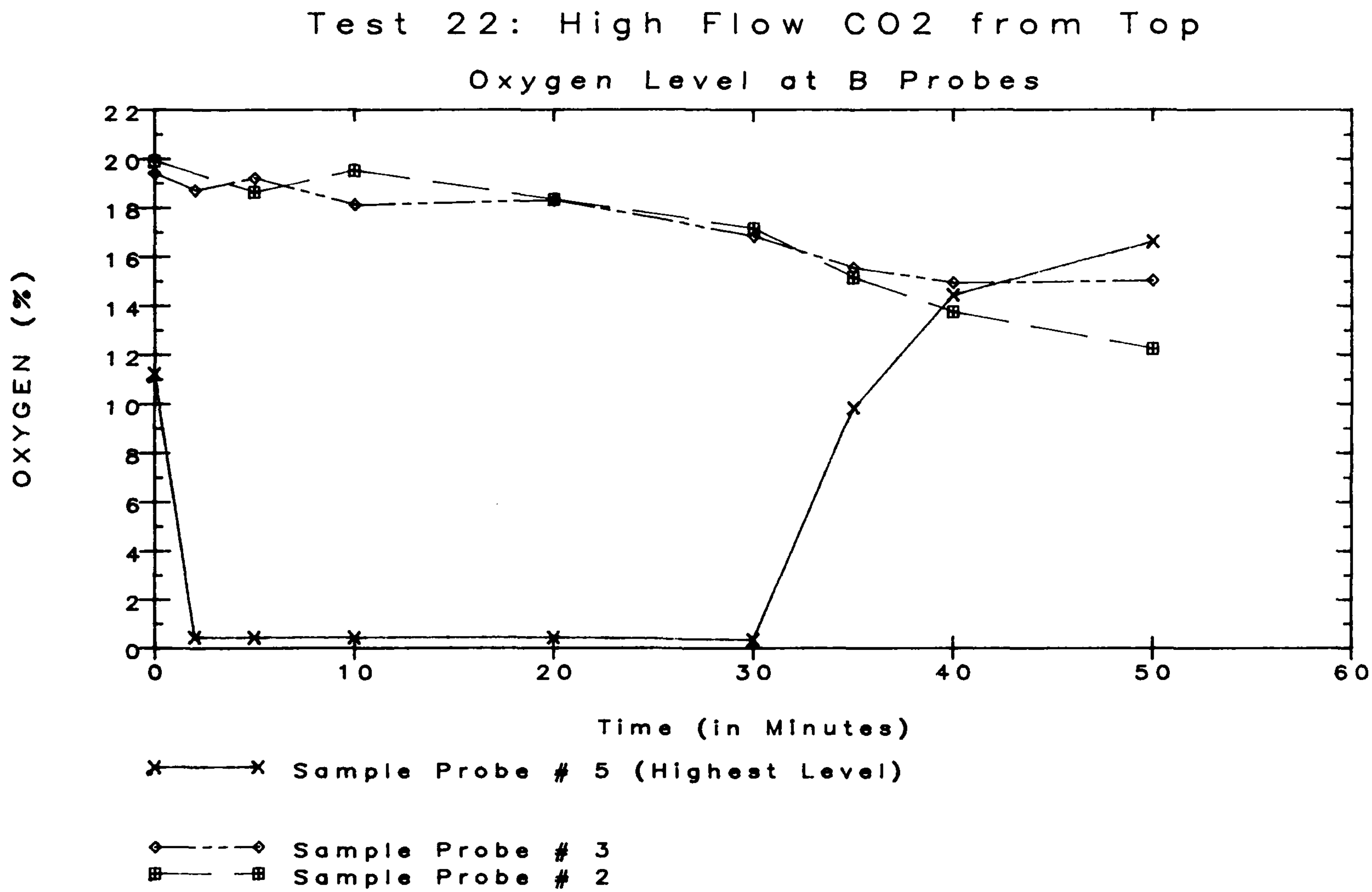


FIGURE 3-9. LARGE SCALE PERMEATION TEST - HIGH FLOW CARBON DIOXIDE INJECTION FROM TOP

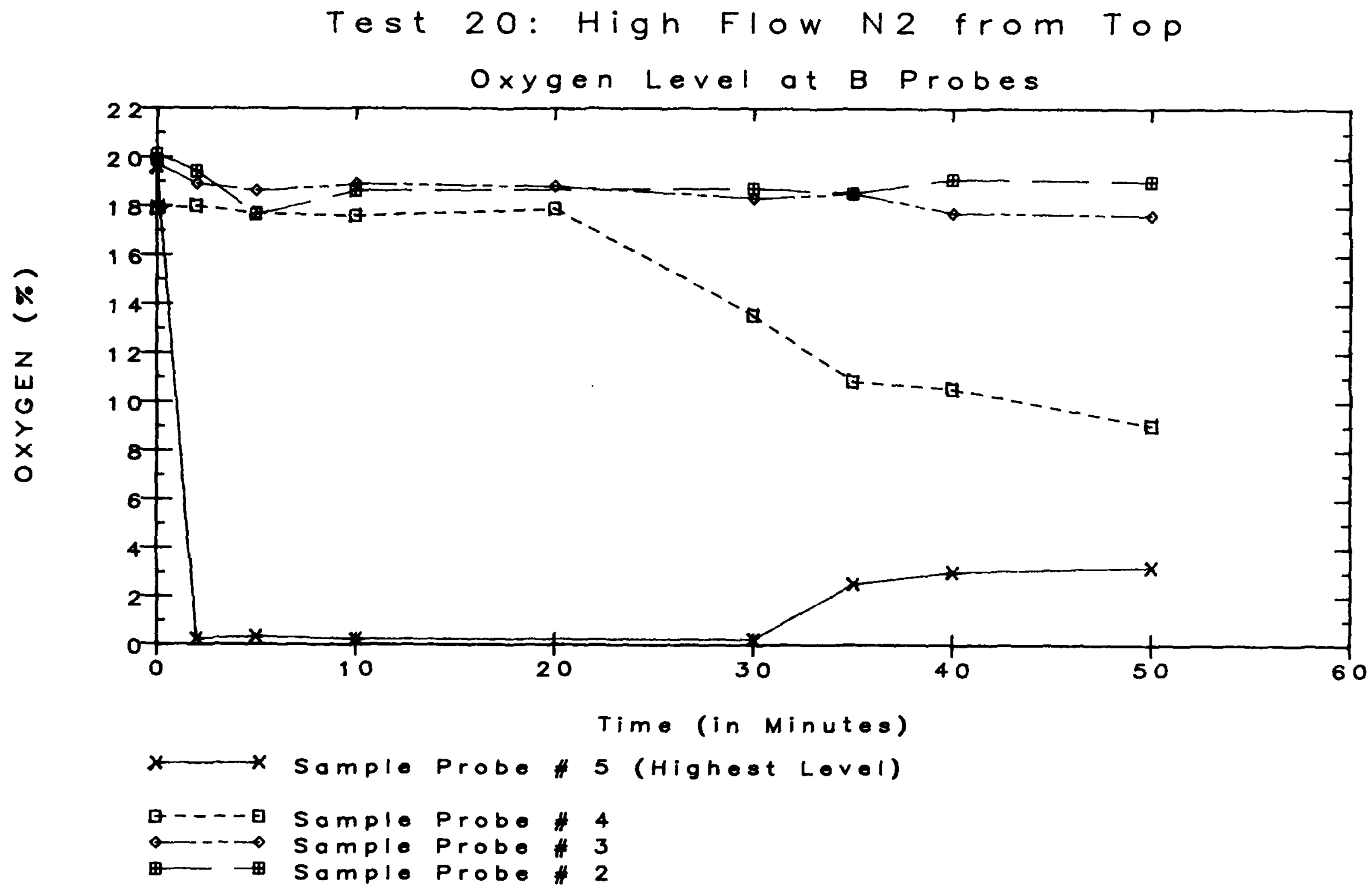


FIGURE 3-10. LARGE SCALE PERMEATION TEST - HIGH FLOW NITROGEN INJECTION FROM TOP

buoyancy between nitrogen and air results in nitrogen having a greater ability to maintain depressed concentrations of oxygen for significantly longer periods of time after the discharge of gas has been stopped.

3.4.4. Low Flow Injection

Similar conclusions on the effectiveness of carbon dioxide and nitrogen can be drawn from reviewing the test data obtained for low flow rate injections during these field tests. One set of figures (3-11 and 3-12), are presented here to show these trends within the coal pile. The flow rate for these injections was 50 cubic feet (1.42 cubic meters) per hour. These figures illustrate that due to the relative neutral buoyancy of air versus nitrogen, the residence time of nitrogen is higher within the coal pile relative to carbon dioxide. The greater density of carbon dioxide causes this gas to sink through the coal pile as a function of time. It therefore cannot maintain depleted oxygen concentrations for extended periods of time unless a continuous discharge of carbon dioxide is maintained. This conclusion can be restated as follow8s: Less nitrogen would have to be discharged relative to carbon dioxide to reduce and maintain depleted oxygen concentrations within the coal pile.

3.4.5. High Flow - 50/50 Carbon Dioxide and Nitrogen Injection

One test sequence was designed to evaluate the effectiveness of a combined discharge of carbon dioxide and nitrogen at 150 cubic feet (4.25 cubic meters) per hour. The gas composition during this discharge was 50 percent carbon dioxide and 50 percent nitrogen by volume. The duration of gas discharge was 30 minutes. Figure 3-13 shows the effect of a discharge of this gas mixture at the mid-point of the coal pile. It demonstrates that this combined gas discharge does significantly reduce oxygen concentrations, maintains these depressed concentrations for a relatively long period of time, and that a larger area of the pile has been affected. This figure also clearly illustrates the sinking of carbon dioxide and "rising" of nitrogen through the pile with respect to time.

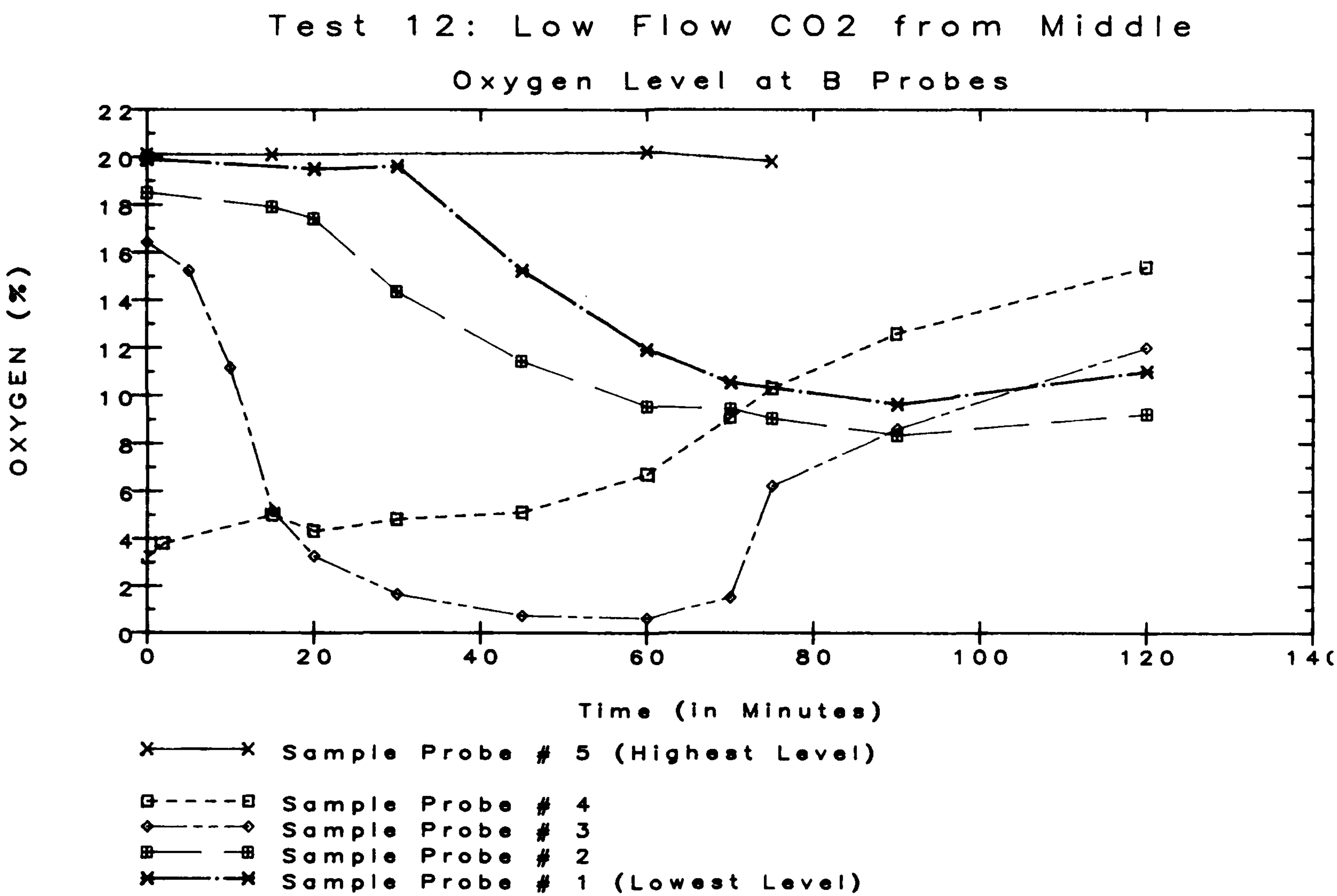


FIGURE 3-11. LARGE SCALE PERMEATION TEST - LOW FLOW CARBON DIOXIDE INJECTION - INJECTION FROM MID-POINT

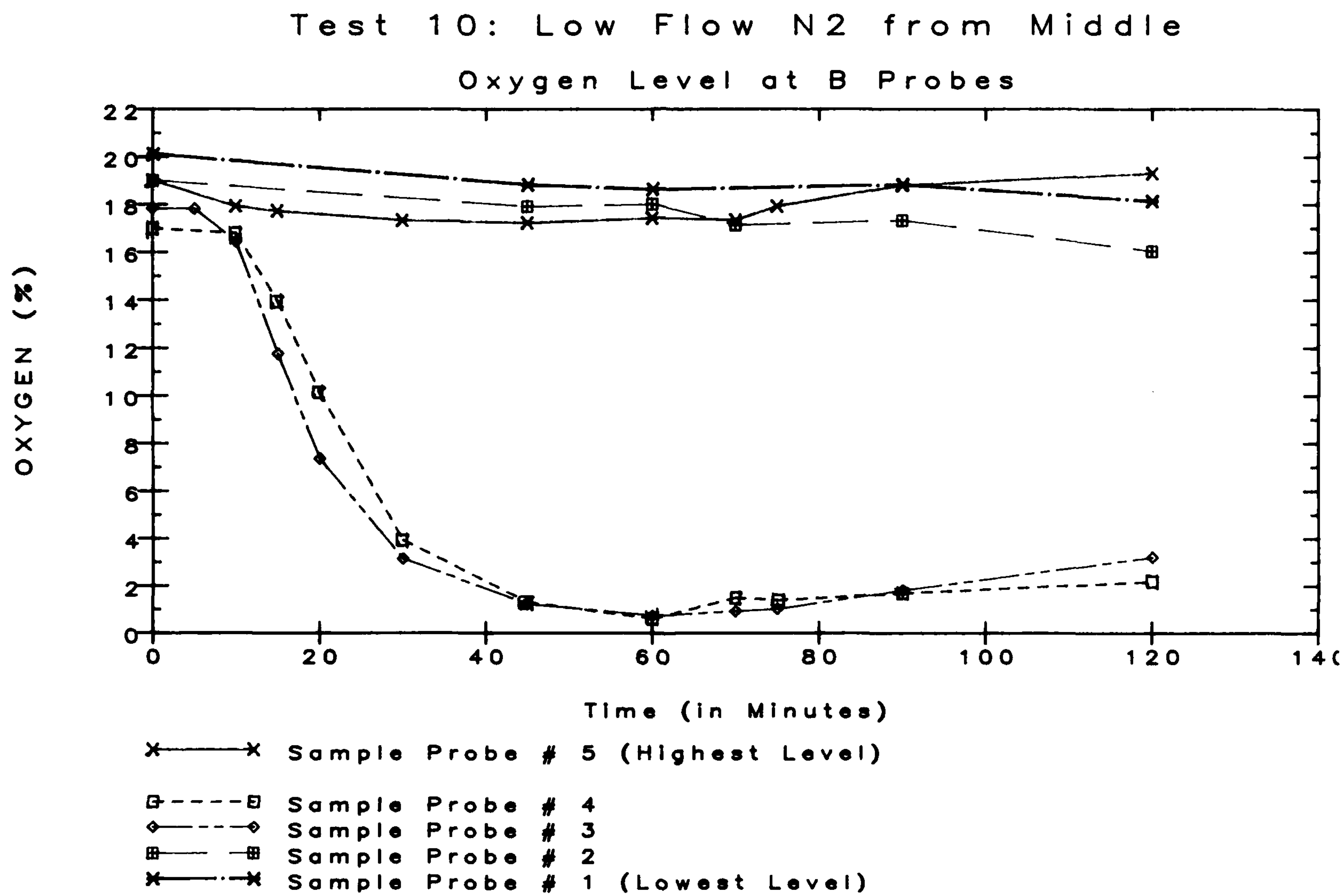


FIGURE 3-12. LARGE SCALE PERMEATION TEST - LOW FLOW NITROGEN INJECTION - INJECTION FROM MID-POINT

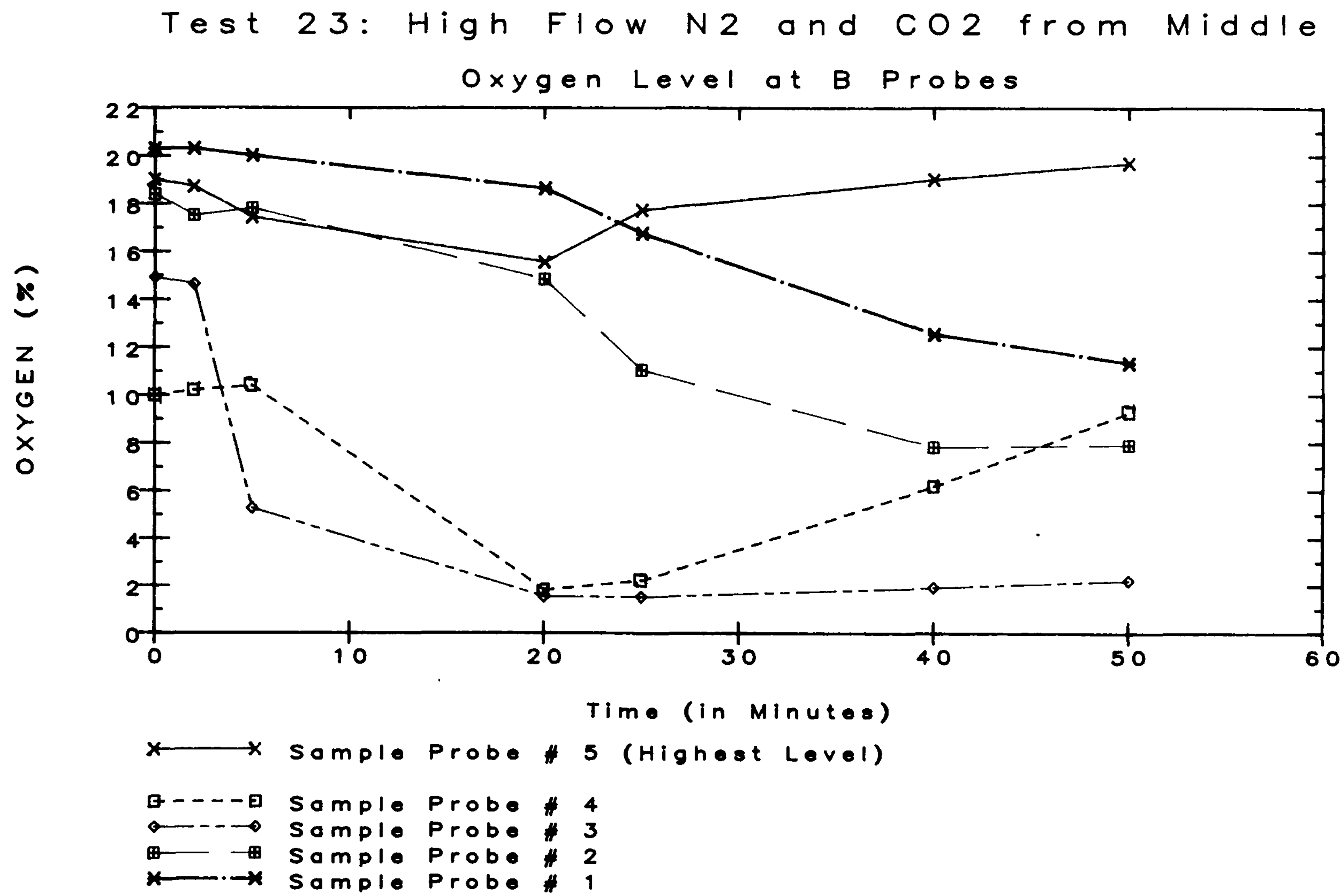


FIGURE 3-13. LARGE SCALE PERMEATION TEST - HIGH FLOW NITROGEN AND CARBON DIOXIDE INJECTION - INJECTION FROM MID-POINT

3.4.6. Wall Effects

As in the case with the flow of any gas or liquid, the medium will seek the path of least resistance. The results of two tests are shown here to illustrate this general trend. Figures 3-14 and 3-15 clearly show that the chambers closest to the walls of the trunk (A & C) are depleted first and that the duration of oxygen depletion is less than that within chamber B. Please note that the 5 probes were oriented 90 degrees with respect to each other as shown in Figure 3-3. Analysis of the data does not indicate any spiraling effect or swirl of gas flow through the column. The conclusion drawn from the analysis of oxygen concentrations in chambers adjacent to the walls of the escape trunk is that for either gas to be effective, it should be discharged from a point within the coal pile and not adjacent to walls, support members, columns, or floor of a cargo hold.

3.4.7 Effects of a "Hot Spot" Within a Coal Pile on Gas Injection

A series of tests were run with "a simulated hot spot" within the coal pile to determine if it would affect the movement of carbon dioxide or nitrogen through the pile. The "hot spot" was located between levels 4 and 5. Gas injection times were for 30 minutes during this sequence. Figures 3-16 and 3-17 are representative of the effects of the heat ball on the oxygen concentrations at level 4 within the coal pile during and after high flow injection of carbon dioxide and nitrogen, respectively, from the top of the pile.

These figures demonstrate again that the oxygen concentration in the center of the pile (B chamber) rises quickly after the carbon dioxide discharge stops. The oxygen concentration is again maintained at low levels 20 minutes after the nitrogen discharge is stopped. In fact, the oxygen concentration was still decreasing. As previously shown, the wall effects are apparent for both the flow of carbon dioxide and nitrogen, i.e., it moves faster along the walls of the escape trunk then through the center of the coal pile.

Figures 3-18 and 3-19 are for mid-point injections of carbon dioxide and nitrogen, respectively, at high flow rates. The data is similar to that shown earlier. The hot spot apparently did not affect the flow of carbon dioxide or nitrogen through the coal pile. Figures 3-20 and 3-21, show a probe labeled H which was located adjacent to the hot spot. It shows that the injected gas has very little effect on the oxygen concentration in the vincinity of the "hot spot".

In both of these sets of figures, it is again readily apparent that depressed oxygen concentrations are maintained within the pile for a longer period of time when nitrogen was the injected gas rather than carbon dioxide.

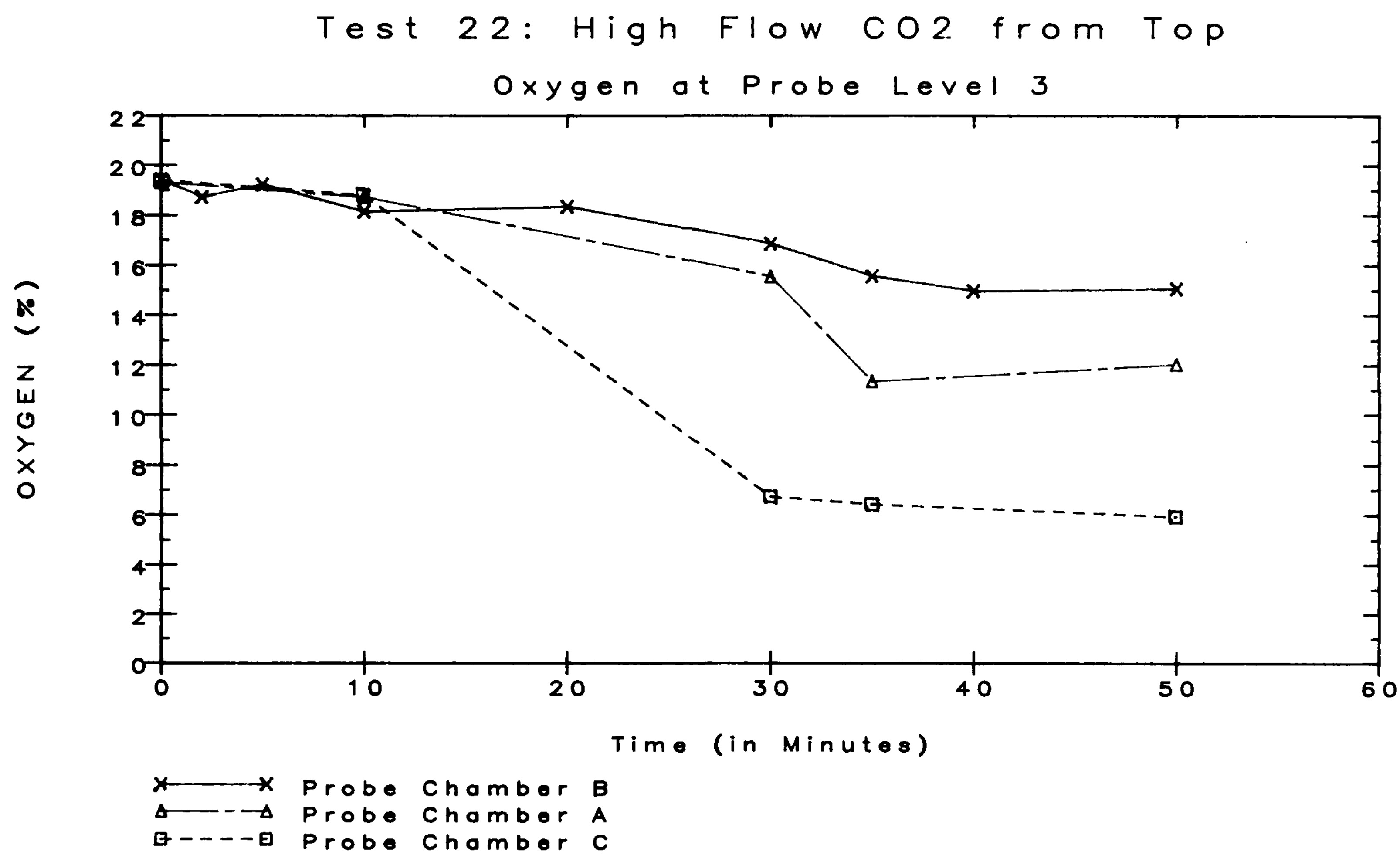


FIGURE 3-14A. LARGE SCALE PERMEATION TEST - WALL EFFECTS WITH CARBON DIOXIDE - EFFECT OF SAMPLING LOCATION - HIGH FLOW CARBON MONOXIDE - INJECTION FROM TOP

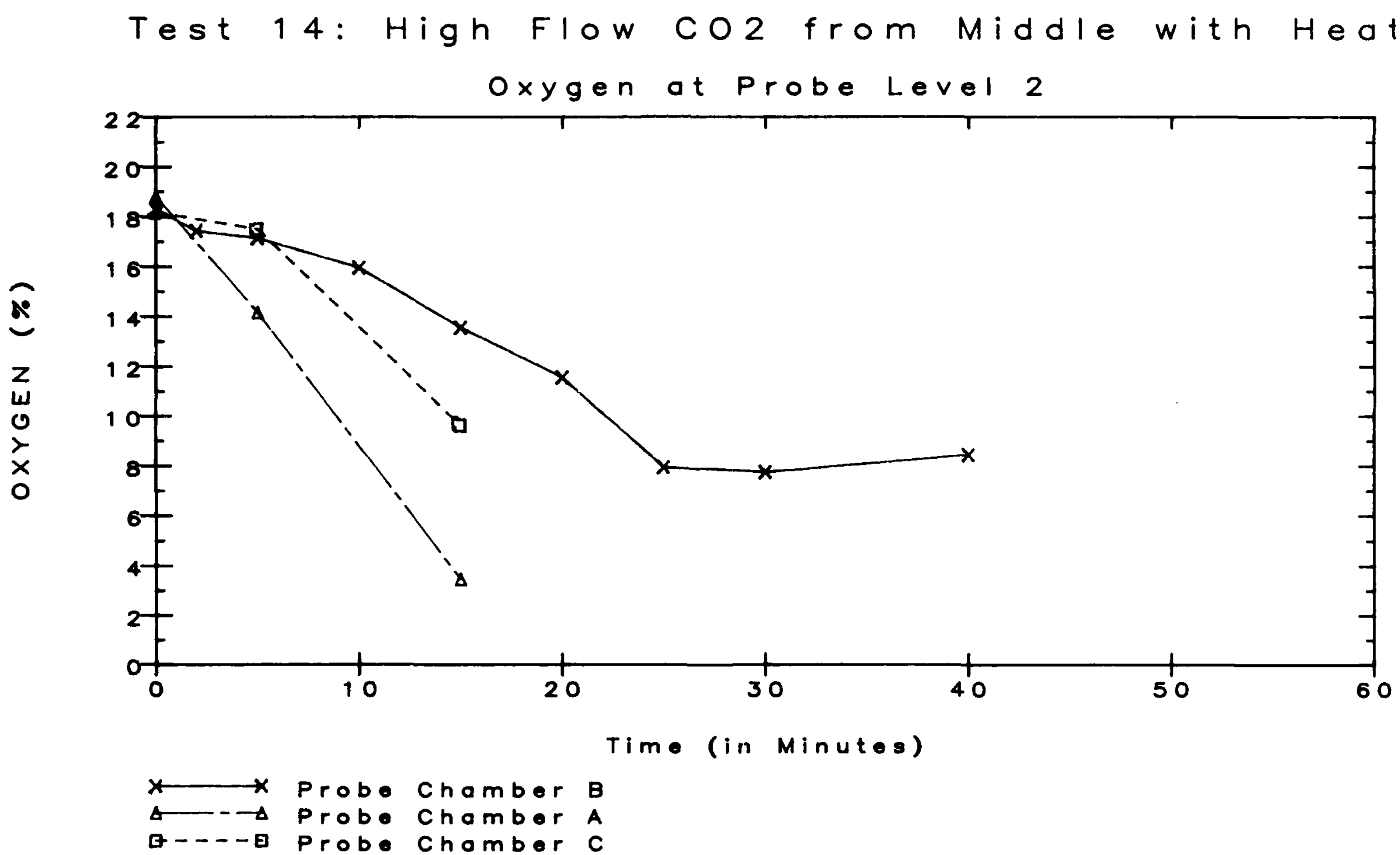


FIGURE 3-14B. LARGE SCALE PERMEATION TEST - WALL EFFECTS WITH CARBON DIOXIDE - EFFECT OF SAMPLING LOCATION - HIGH FLOW CARBON MONOXIDE - INJECTION FROM MID-POINT

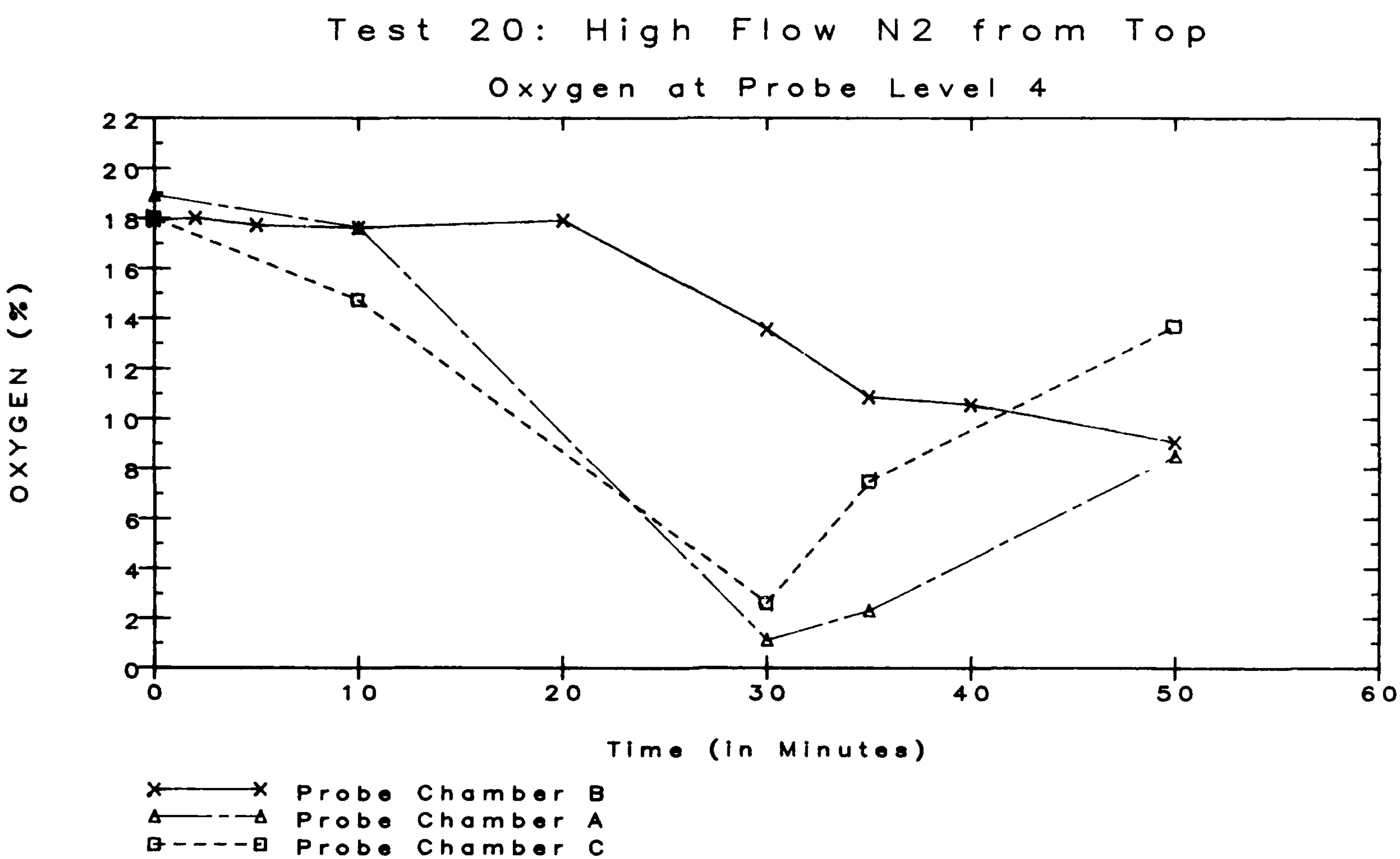


FIGURE 3-15A. LARGE SCALE PERMEATION TEST - WALL EFFECTS WITH NITROGEN - EFFECT OF SAMPLING LOCATION - HIGH FLOW NITROGEN - INJECTION FROM TOP

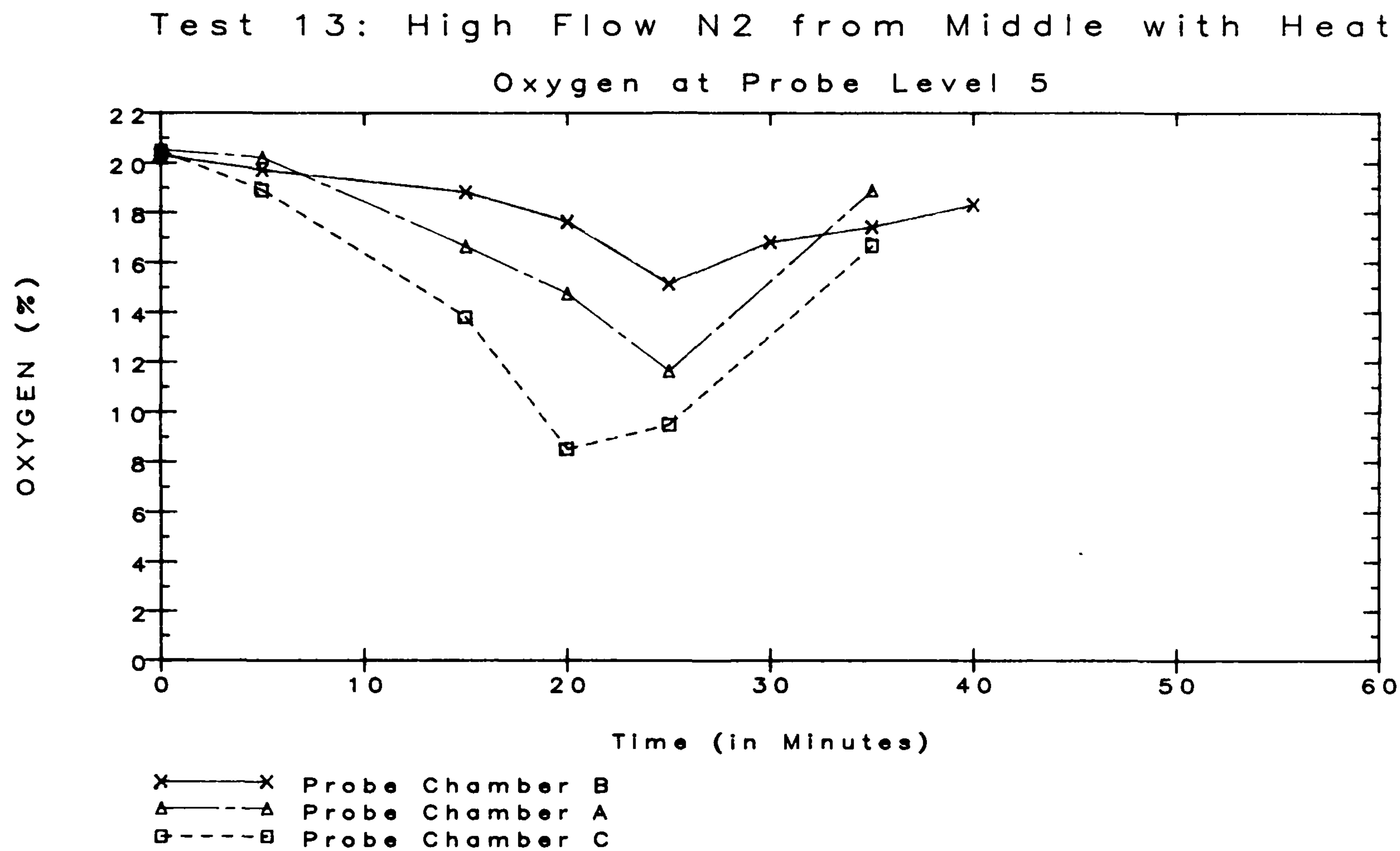


FIGURE 3-15B. LARGE SCALE PERMEATION TEST - WALL EFFECTS WITH NITROGEN - EFFECT OF SAMPLING LOCATION - HIGH FLOW NITROGEN - INJECTION FROM MID-POINT

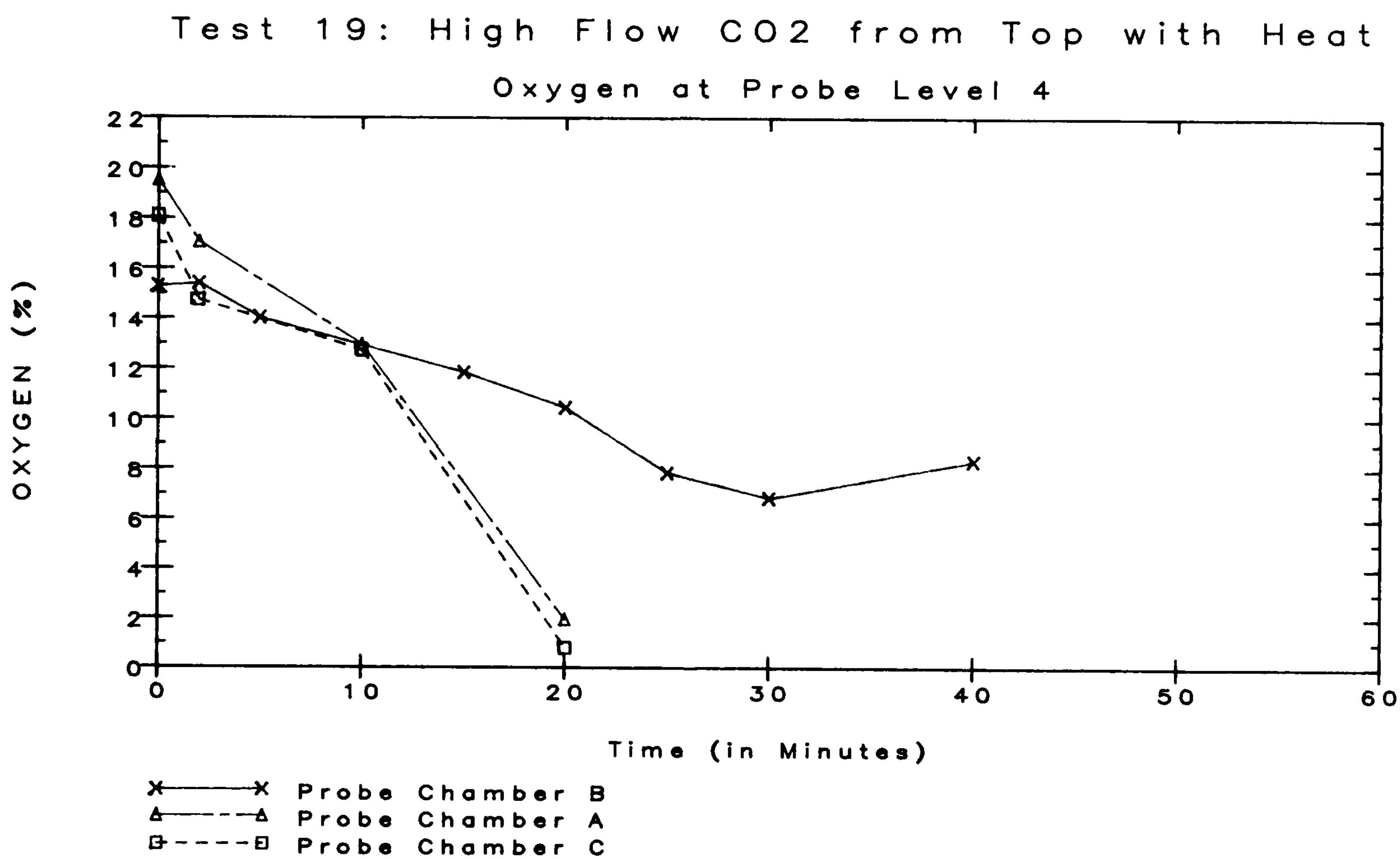


FIGURE 3-16. LARGE SCALE PERMEATION TEST - "HOT SPOT" EFFECTS WITH CARBON DIOXIDE - HIGH FLOW INJECTION FROM TOP OF COAL PILE

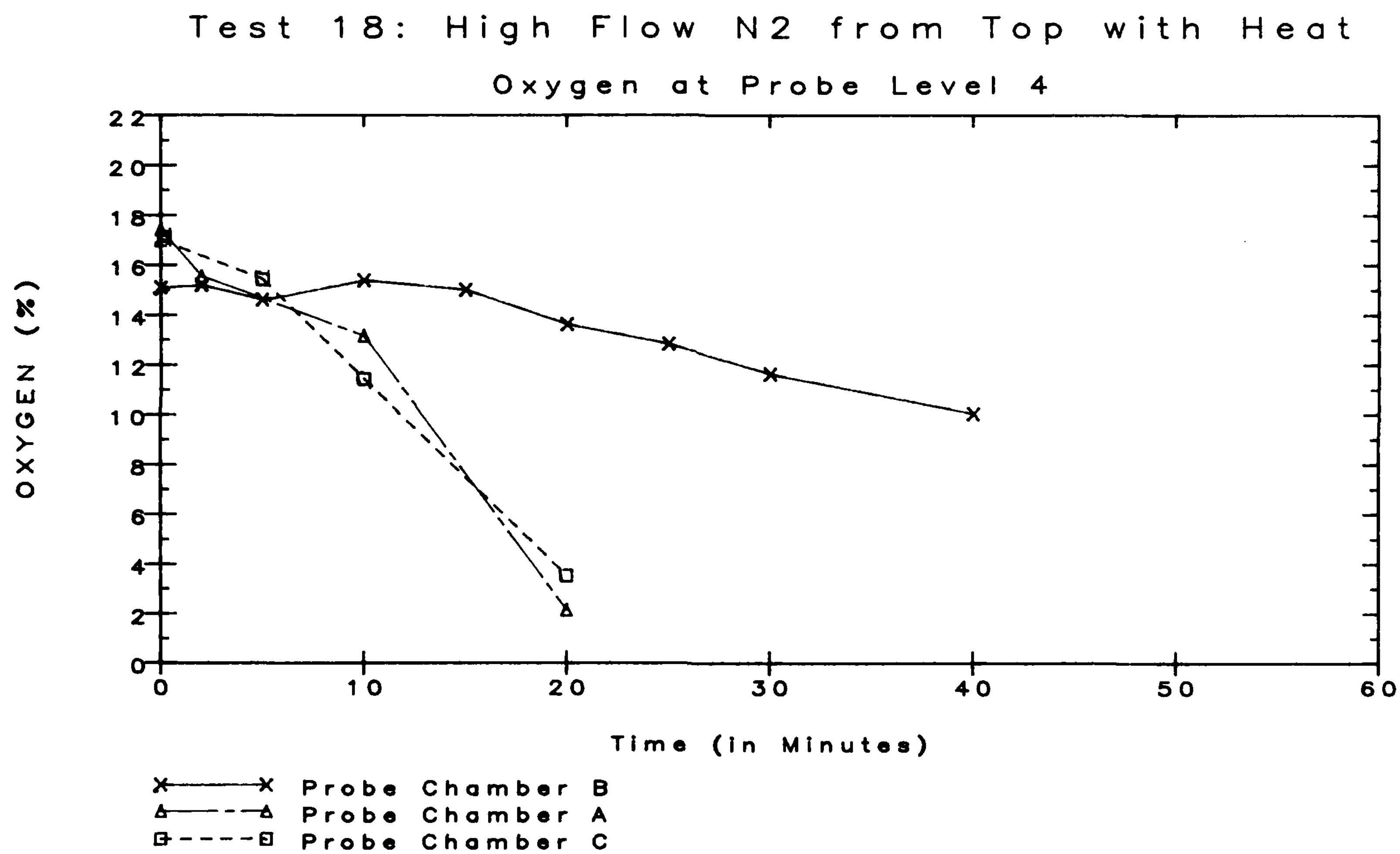


FIGURE 3-17. LARGE SCALE PERMEATION TEST - "HOT SPOT" EFFECTS WITH NITROGEN - HIGH FLOW INJECTION FROM TOP OF COAL PILE

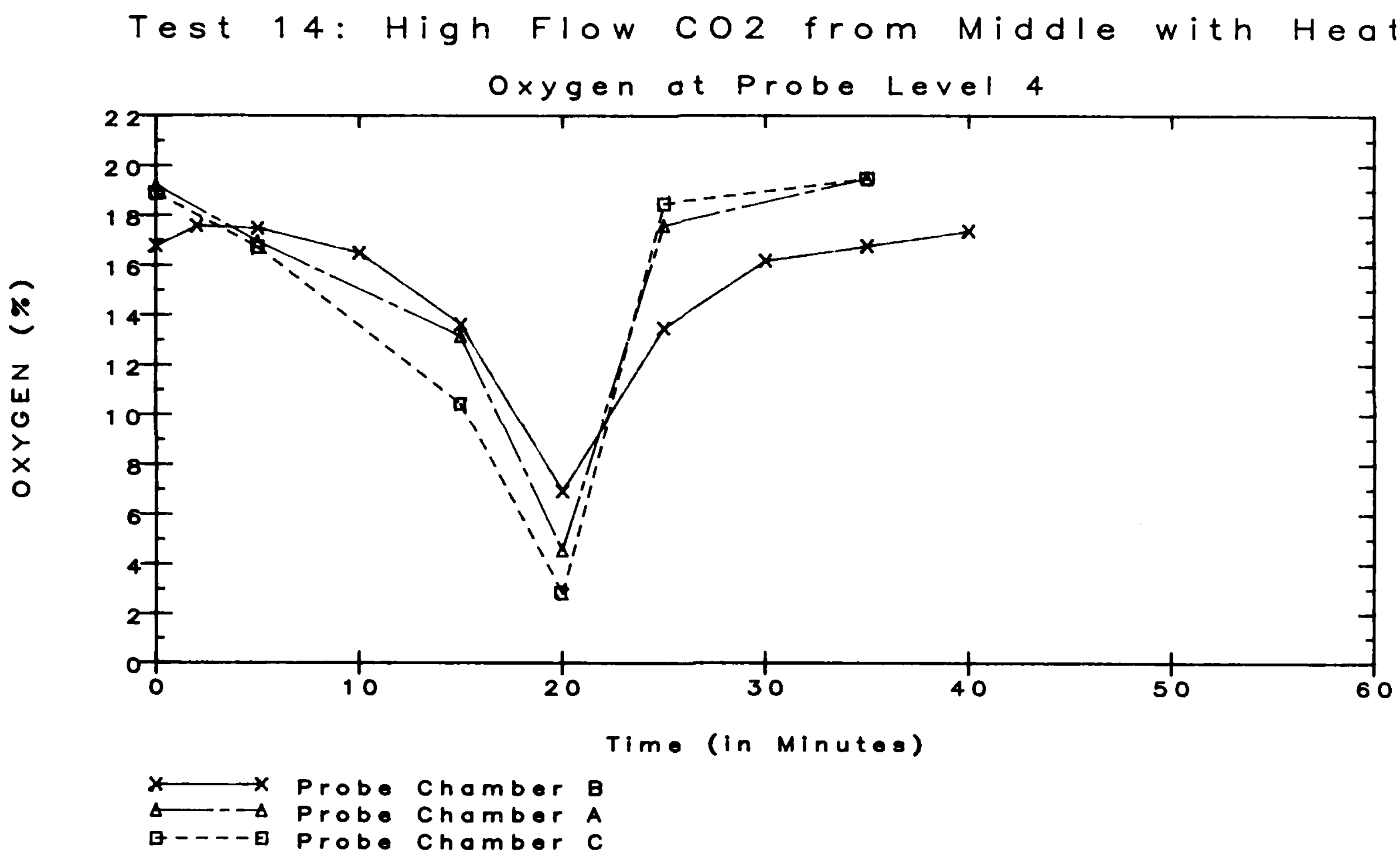


FIGURE 3-18. LARGE SCALE PERMEATION TEST - "HOT SPOT" EFFECTS WITH CARBON DIOXIDE - HIGH FLOW INJECTION FROM MID-POINT OF COAL PILE

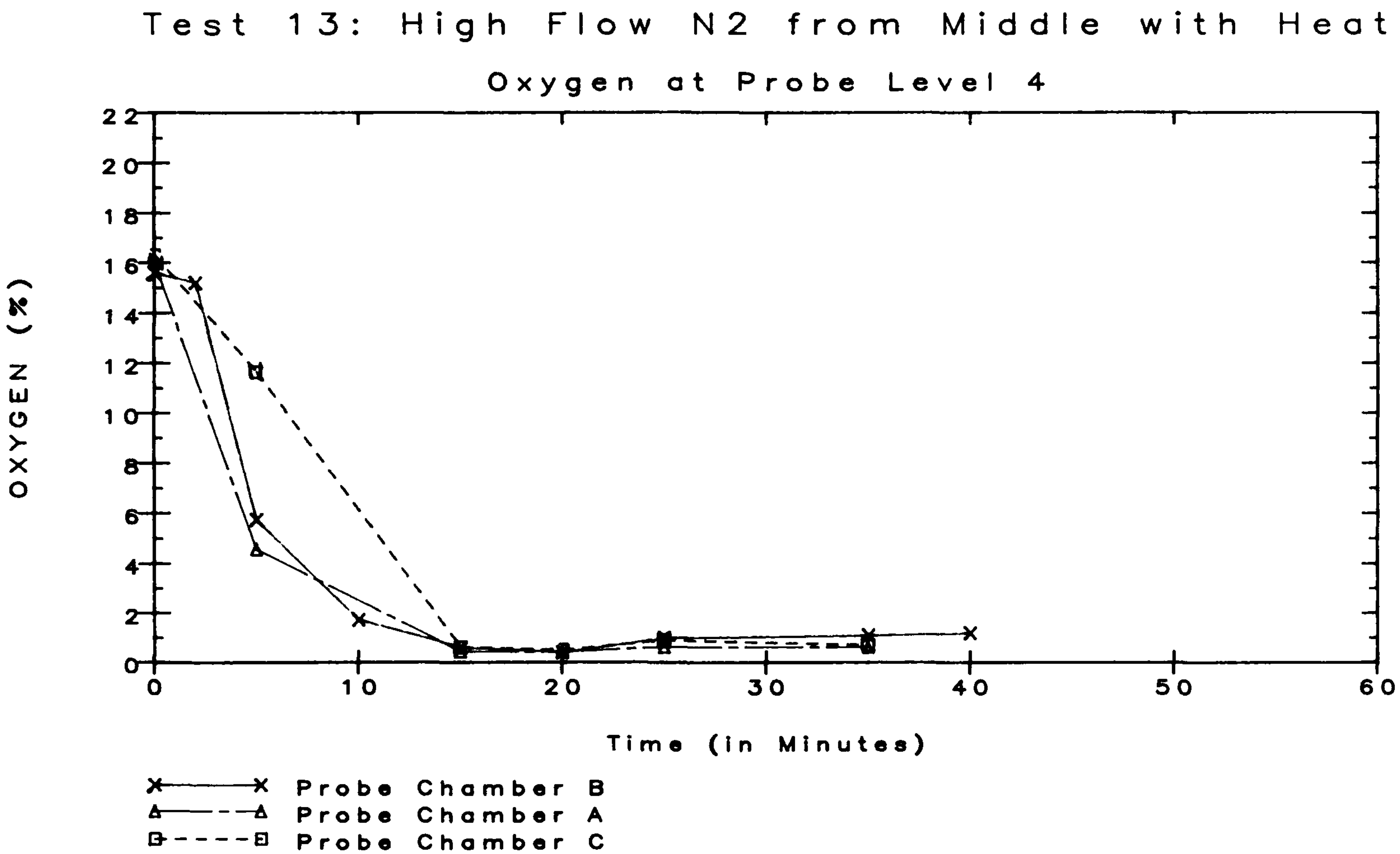


FIGURE 3-19. LARGE SCALE PERMEATION TEST - "HOT SPOT" EFFECTS WITH NITROGEN - HIGH FLOW INJECTION FROM MID-POINT OF COAL PILE

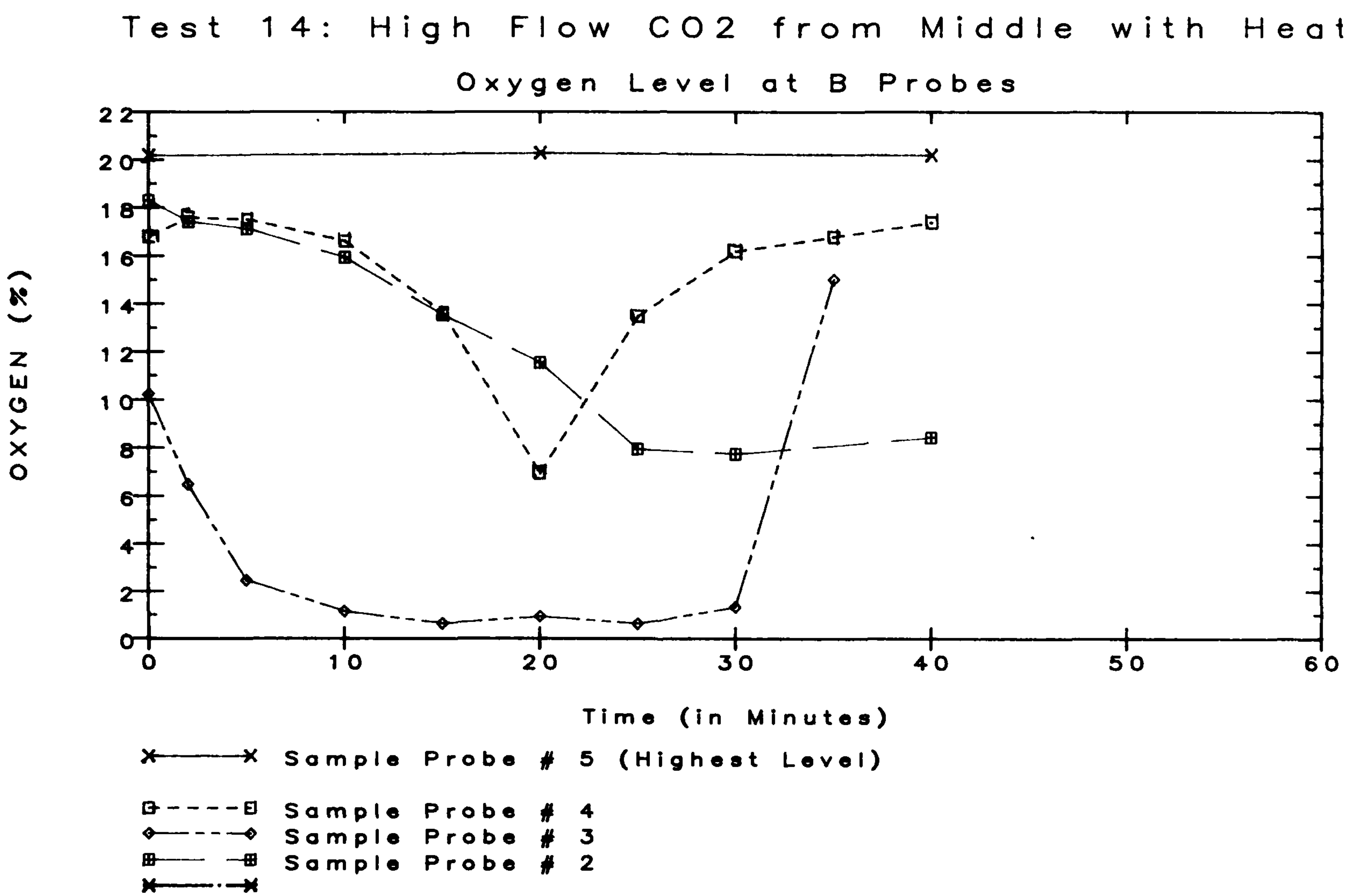


FIGURE 3-20. LARGE SCALE PERMEATION TEST - INJECTION NEAR "HOT SPOT" - HIGH FLOW INJECTION OF CARBON DIOXIDE

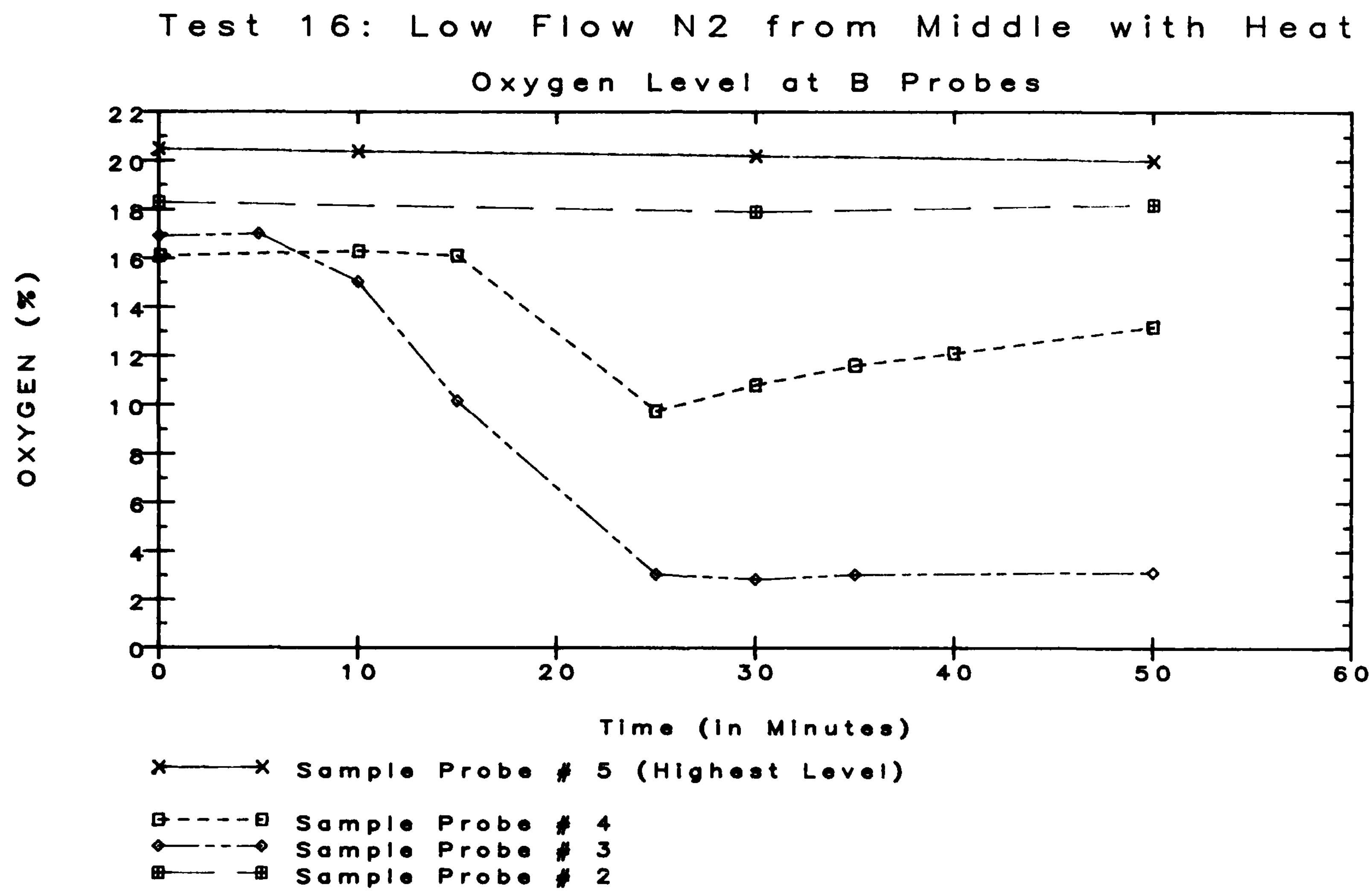


FIGURE 3-21. LARGE SCALE PERMEATION TEST - INJECTION NEAR "HOT SPOT" - LOW FLOW INJECTION OF NITROGEN

3.5 Summary of Permeation Studies

From the laboratory and field studies the following conclusions can be drawn regarding the movement of carbon dioxide and nitrogen through a coal pile:

a. carbon dioxide sinks based on its relatively high density as compared to air. This sinking rate is substantial and it is expected that as it sinks, it draws air back quickly into the vacated area by normal convective flow. Figure 3-22 illustrates the sinking characteristics of carbon dioxide through the coal pile. When the carbon dioxide injection at the top of the pile stops, its concentration at that level (level 5) quickly drops off. This is followed by a corresponding increase in carbon dioxide concentration at depth with the pile. Figure 3-23 indicates that carbon dioxide will sink over time even if it is injected at or near the bottom. This clearly illustrates why oxygen levels return quickly at the bottom of the coal column after carbon dioxide injection has stopped (refer to Figure 3-5) since it rapidly settles and must draw air back into the pile. On the other hand Figure 3-6 clearly shows that nitrogen, having a relatively neutral buoyancy, remains longer and oxygen levels are depleted for a longer period of time.

b. nitrogen moves through the coal pile by normal diffusion. Increasing the injection flow rate will increase the speed of oxygen depletion. As a result of its "nearly neutral buoyancy," as compared to air, it does not rise through the coal as quickly as carbon dioxide sinks.

c. Wall effects are critical. Any discharge of gas will preferentially follow the path of least resistance; therefore, any use of an inert gas injection system to combat coal fires should be from a point within the cargo, preferably at its midpoint.

d. Although not tested, the data indicates that blanketing a cargo hold with carbon dioxide, unless it is a continuous and sustained discharge, probably is ineffective in combating fires. Once the discharge stops, the carbon dioxide will settle and if there is any opening at the base of the cargo hold, will leak out. As carbon dioxide sinks through the coal cargo, air will be brought into the coal pile as a result of normal convective flow.

e. nitrogen is more effective in maintaining depressed oxygen concentrations within the coal pile for a longer period of time than carbon dioxide.

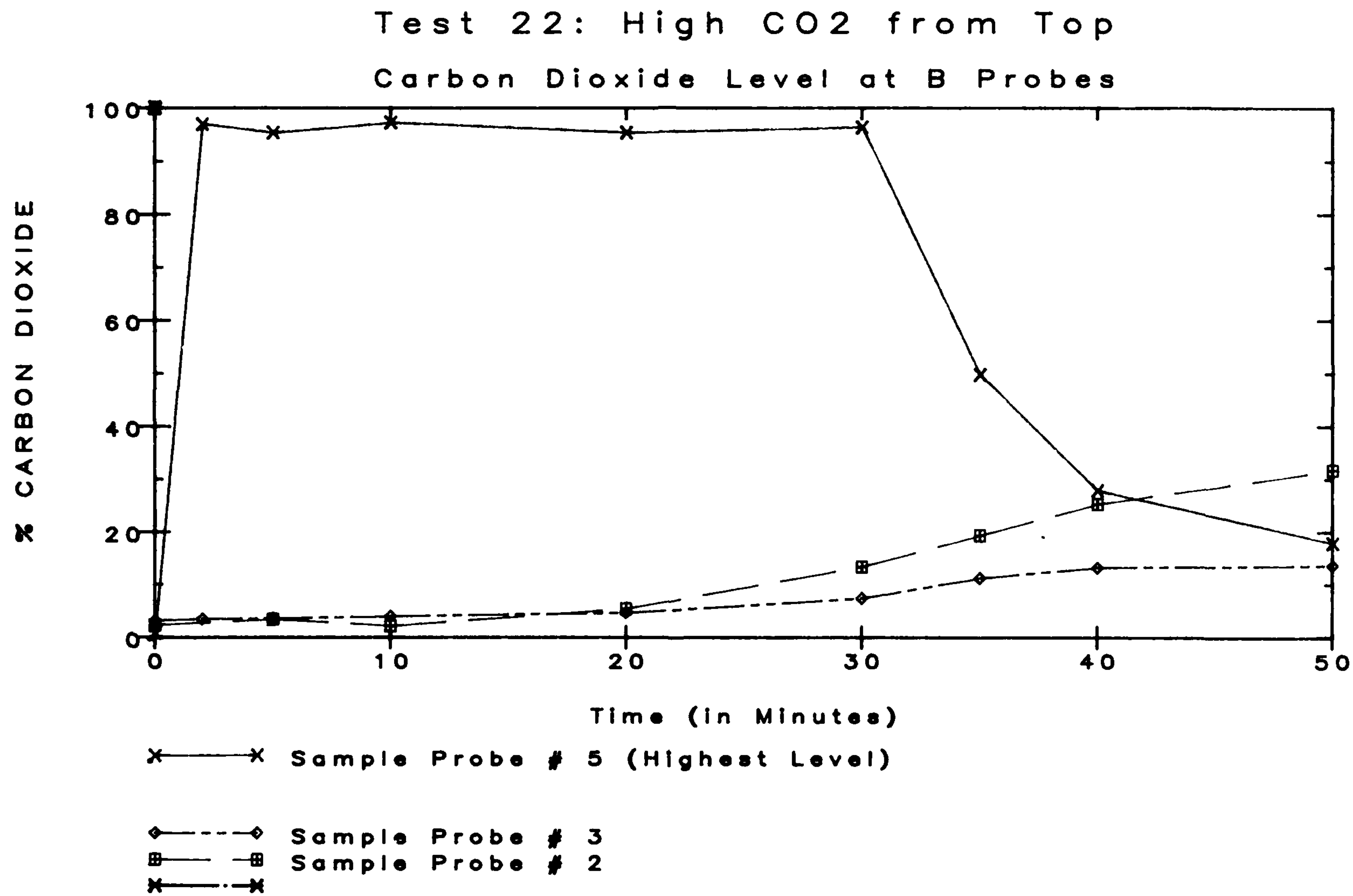


FIGURE 3-22. LARGE SCALE PERMEATION TEST - CARBON DIOXIDE INJECTION FROM TOP

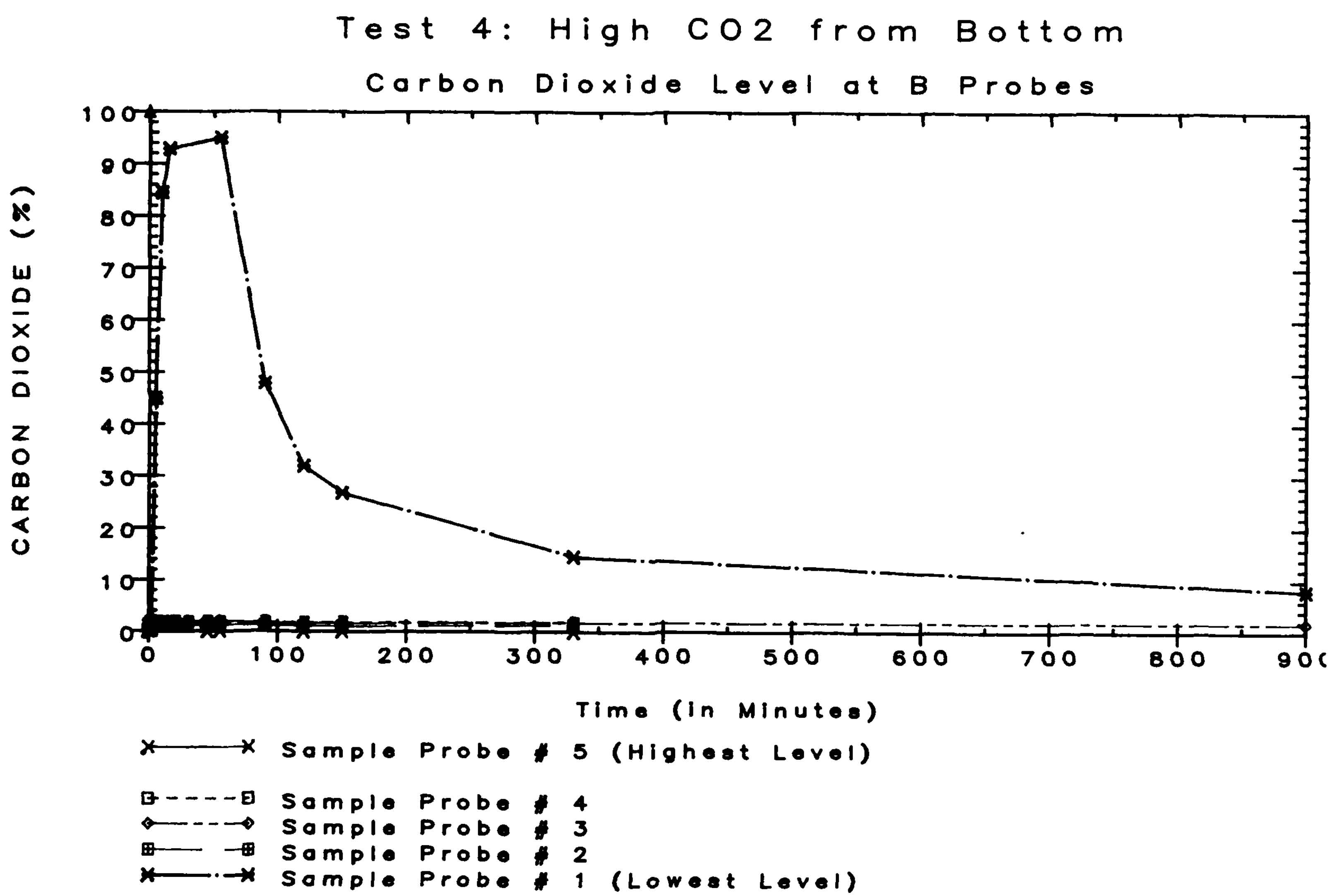


FIGURE 3-23. LARGE SCALE PERMEATION TEST - CARBON DIOXIDE INJECTION FROM BOTTOM

f. No significant influence on the behavior and movement of either carbon dioxide or nitrogen was detected as the result of a "hot spot" being present within the coal pile. Neither gas displaced much oxygen in the immediate vicinity of the "hot spot". A larger or more intense "hot spot" could have a significant effect on the extinguishment of a coal pile fire. Additional testing with larger "hot spots" is required to verify these preliminary conclusions which were drawn from a limited data set.

4.0 FIRE QUENCH TESTS

4.1 Objective

The fire quench tests were designed to study the behavior of carbon dioxide and nitrogen when injected into a hot coal fire. This study was conducted using the same small-scale test chamber used for the spontaneous ignition tests.

4.2 Test Procedures

The coal chamber was hand-packed and each of the probes was placed individually to insure proper location. The heater was activated, along with the forced ventilation system to supply the fire with sufficient oxygen. When it was determined that a well-established high temperature coal fire had been obtained, one of the two extinguishing agents (carbon dioxide or nitrogen) was injected at a high flow rate from cylinders. At the conclusion of each test, the vents were opened to release volatile gases. The chamber was emptied and any "hot spots" were extinguished.

4.3 Data Analysis and Test Results

The fire quench data was analyzed with respect to various gas levels (oxygen, carbon monoxide, carbon dioxide, and methane) and temperatures during the extinguishing gas injections. Temperatures from thermocouples along each axis were averaged and plotted versus time. Temperatures for tests 2 and 3 averaged between 60°C (140°F) and 70°C (158°F). Temperatures for tests 4 and 5 were in the 100°C (212°F) to 400°C (752°F) range. Carbon dioxide was injected in tests 2 and 4 while nitrogen was injected in tests 3 and 5. Figure 4-1 presents a typical temperature time history for carbon dioxide injection. When the vents were closed the temperature rose steadily. When the carbon dioxide was injected, there was a quick rise in temperature followed by a very sharp drop in temperature. As the pressure in the carbon dioxide cylinder dropped, the temperature began to rise until it reached approximately the same temperature as before the carbon dioxide injection began.

Figure 4-2a. depicts the concentration of oxygen and carbon dioxide during the carbon dioxide injection and Figure 4-2b. shows the concentration of carbon monoxide and methane during this test. The oxygen concentration was not completely depleted by the carbon dioxide injection, but did remain below 10 percent.

Figure 4-3 is representative of all the thermocouple channels for a fire quench test using nitrogen. When the vents were closed the temperature gradually began to cool down. The most notable difference between carbon dioxide and nitrogen was the temperature response. When the nitrogen was injected, there was a delayed and gradual temperature rise that fell off as the pressure in the nitrogen cylinder dropped. Like the carbon dioxide injection, the temperature returned to approximately the

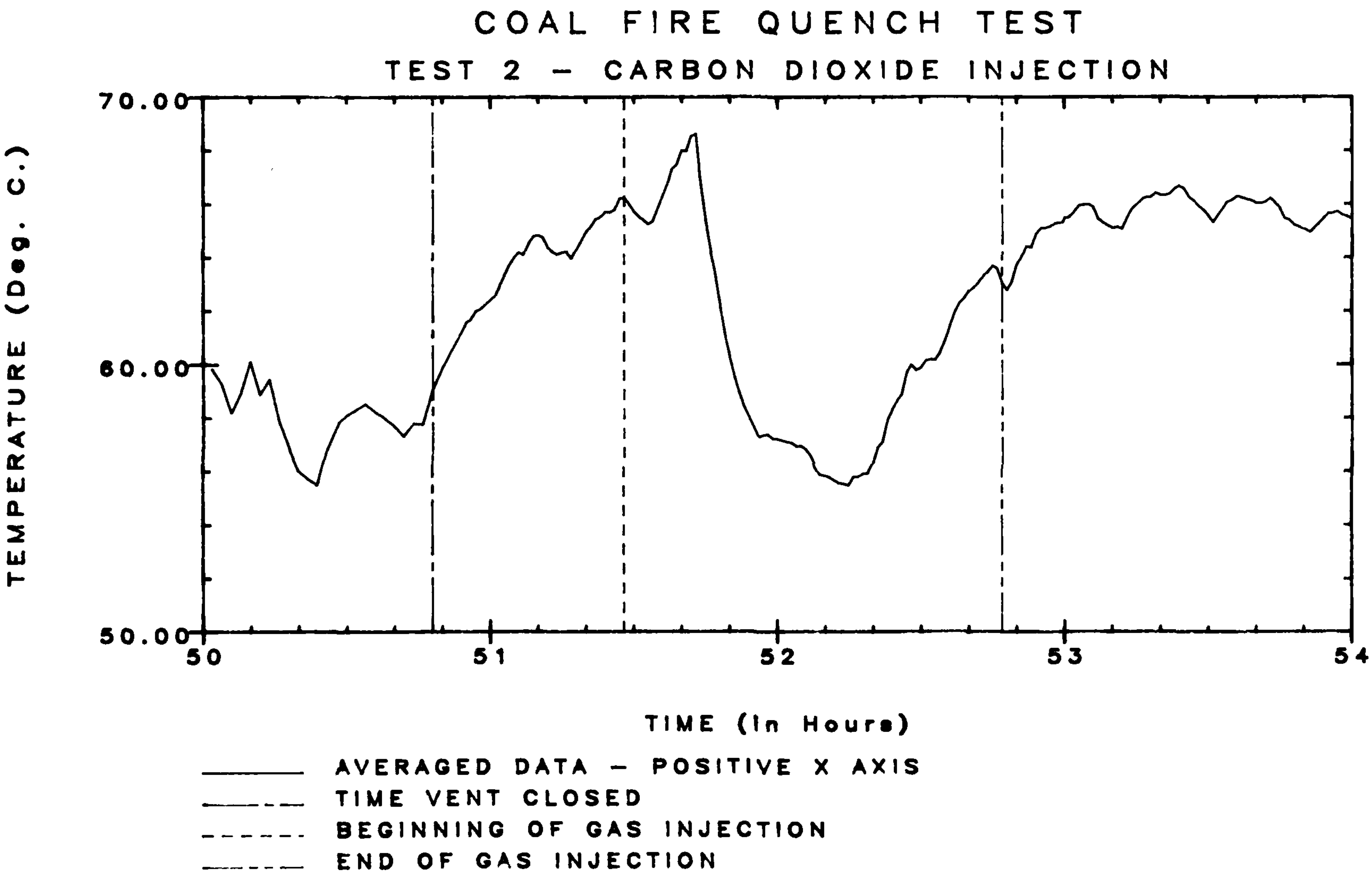


FIGURE 4-1. FIRE QUENCH TEST WITH CARBON DIOXIDE INJECTION - TEMPERATURE HISTORY

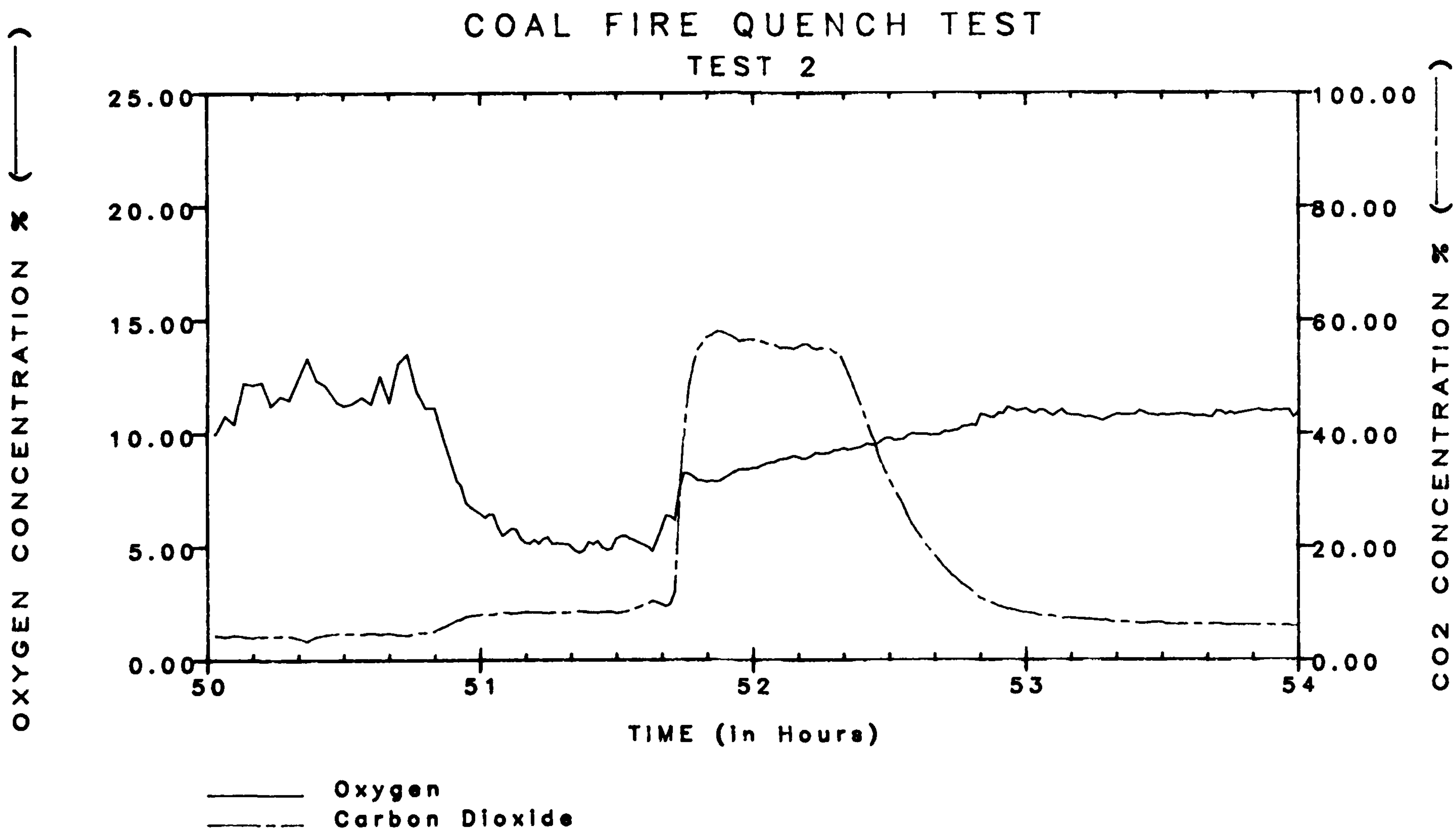


FIGURE 4-2A. FIRE QUENCH TEST WITH CARBON DIOXIDE INJECTION - OXYGEN AND CARBON DIOXIDE CONCENTRATIONS

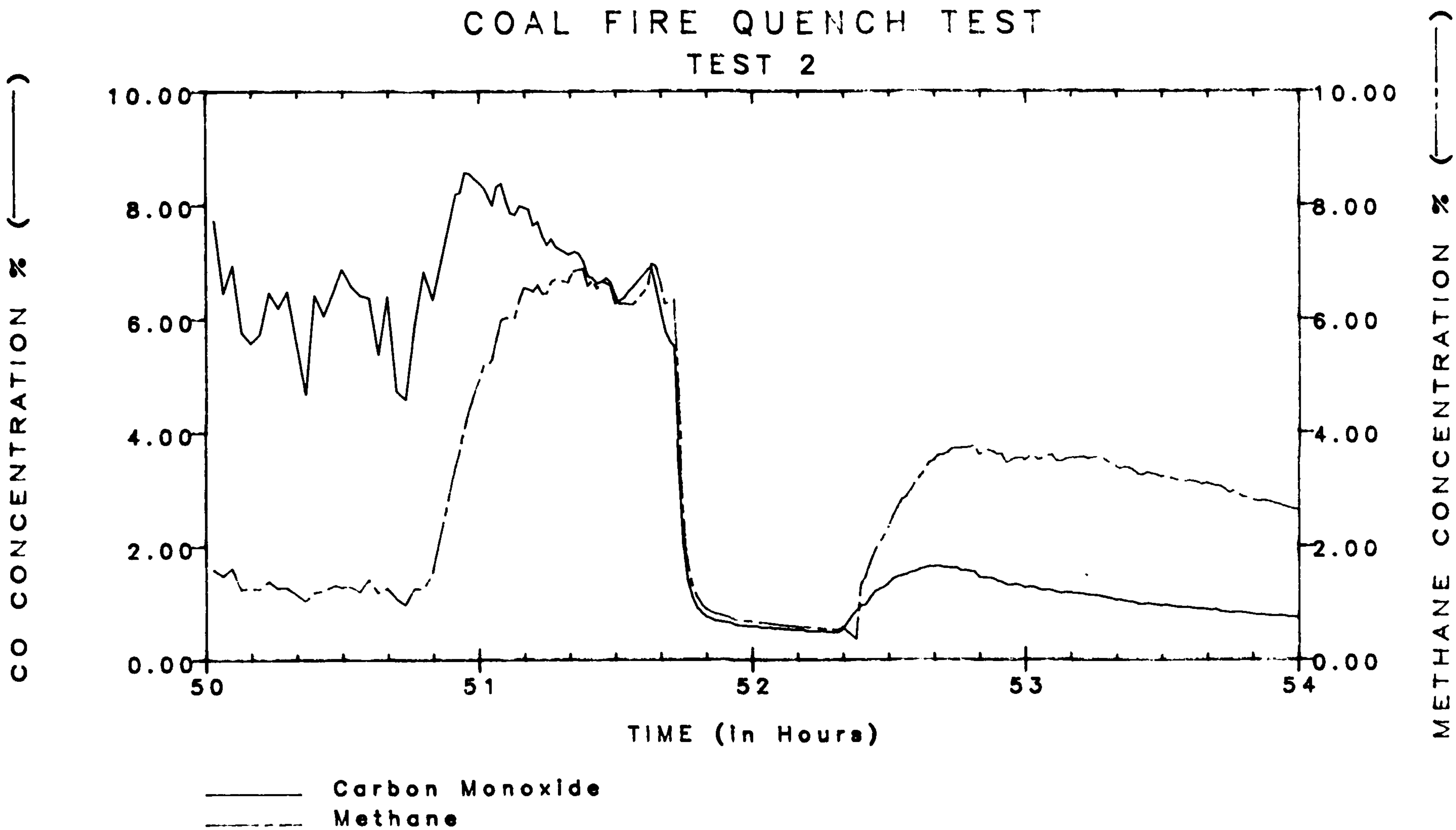


FIGURE 4-2B. FIRE QUENCH TEST WITH CARBON DIOXIDE INJECTION - CARBON MONOXIDE AND METHANE CONCENTRATIONS

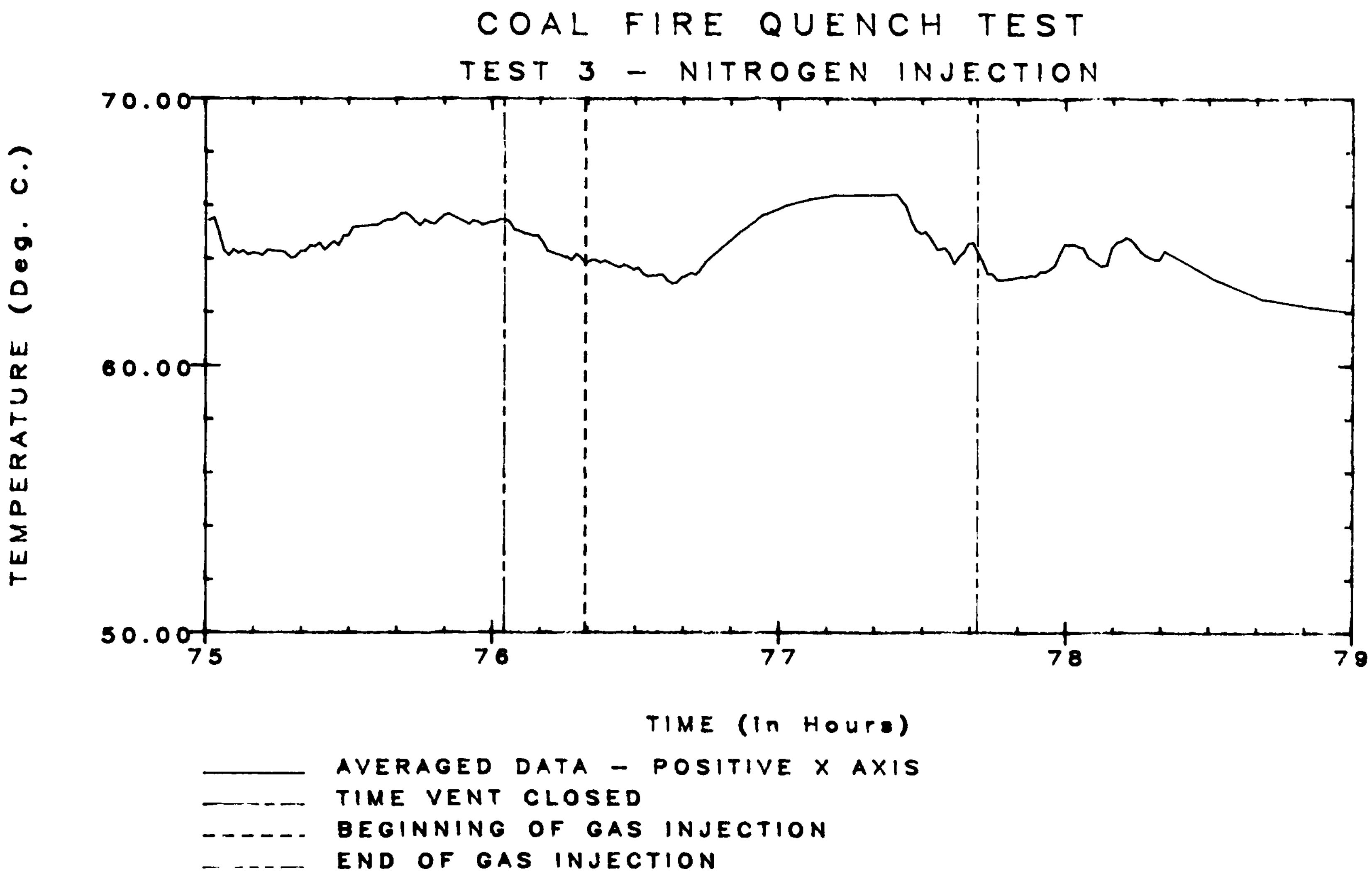


FIGURE 4-3. FIRE QUENCH TEST WITH NITROGEN INJECTION - TEMPERATURE HISTORY

same temperature as before the injection began. The difference in response can be attributed to the temperature difference at which the two gases are injected.

Figures 4-4 and 4-5 show temperature histories for tests 4 and 5 which were in the 100°C (212°F) to 400°C (752°F) range. These graphs are representative of all the thermocouples in these tests. The temperature response to carbon dioxide injection is different in this hotter test. When the vents were closed, the temperature dropped sharply (see Figure 4-5). In the cooler test, the temperature rose after the vents were closed (see Figure 4-1). The temperature dropped because the fire had been stoked to a higher temperature than could be maintained without constant forced ventilation. It was returning to an equilibrum temperature. In the cooler test the fire was growing without the assistance of forced ventilation. The behavior was consistent between the two tests after the carbon dioxide was injected. There was a quick rise followed by a steady drop in temperature. After the injection was complete, the temperature returned to baseline temperature. Figure 4-5 shows the response of the nitrogen injection. Since the graph shows a steady fall to a baseline temperature, little can be deduced regarding the behavior due to the nitrogen injection.

Figure 4-6 shows the concentration of oxygen and carbon dioxide and Figure 4-7 illustrates the carbon monoxide and methane levels for test 4 (carbon dioxide injection). The oxygen decreased rapidly from an already low concentration when the vents were closed. Carbon dioxide completely flushed all other gases out. The concentrations of carbon monoxide and methane dropped to less than one percent during the carbon dioxide injection.

Figures 4-8 and 4-9 show the gas concentrations for the nitrogen injection in test 5. The figures show that the gases are depleted during the nitrogen injection. After the injection, both oxygen and carbon dioxide returned to their pre-injection baseline concentrations.

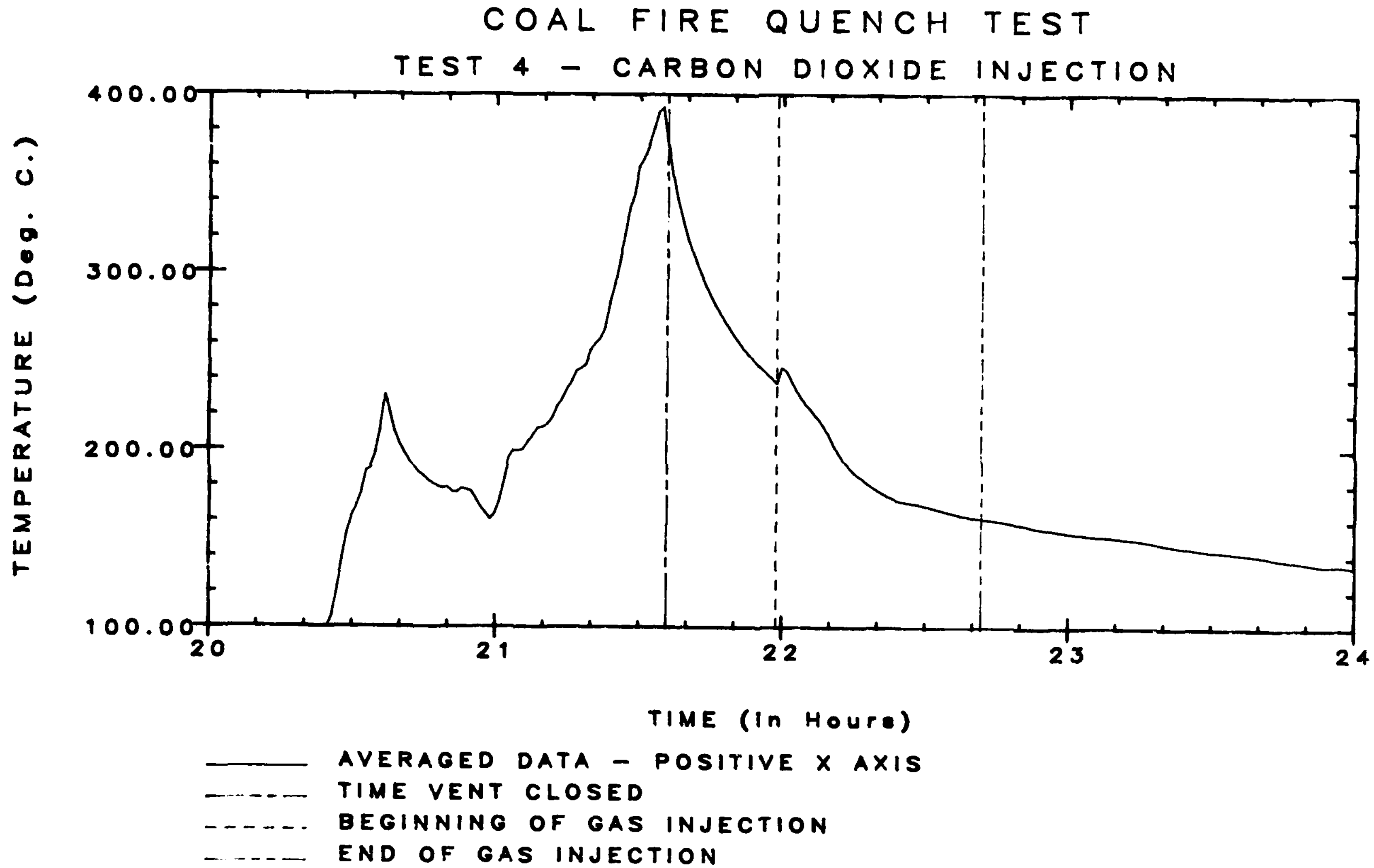


FIGURE 4-4. HOT FIRE QUENCH TEST WITH CARBON DIOXIDE INJECTION - TEMPERATURE HISTORY

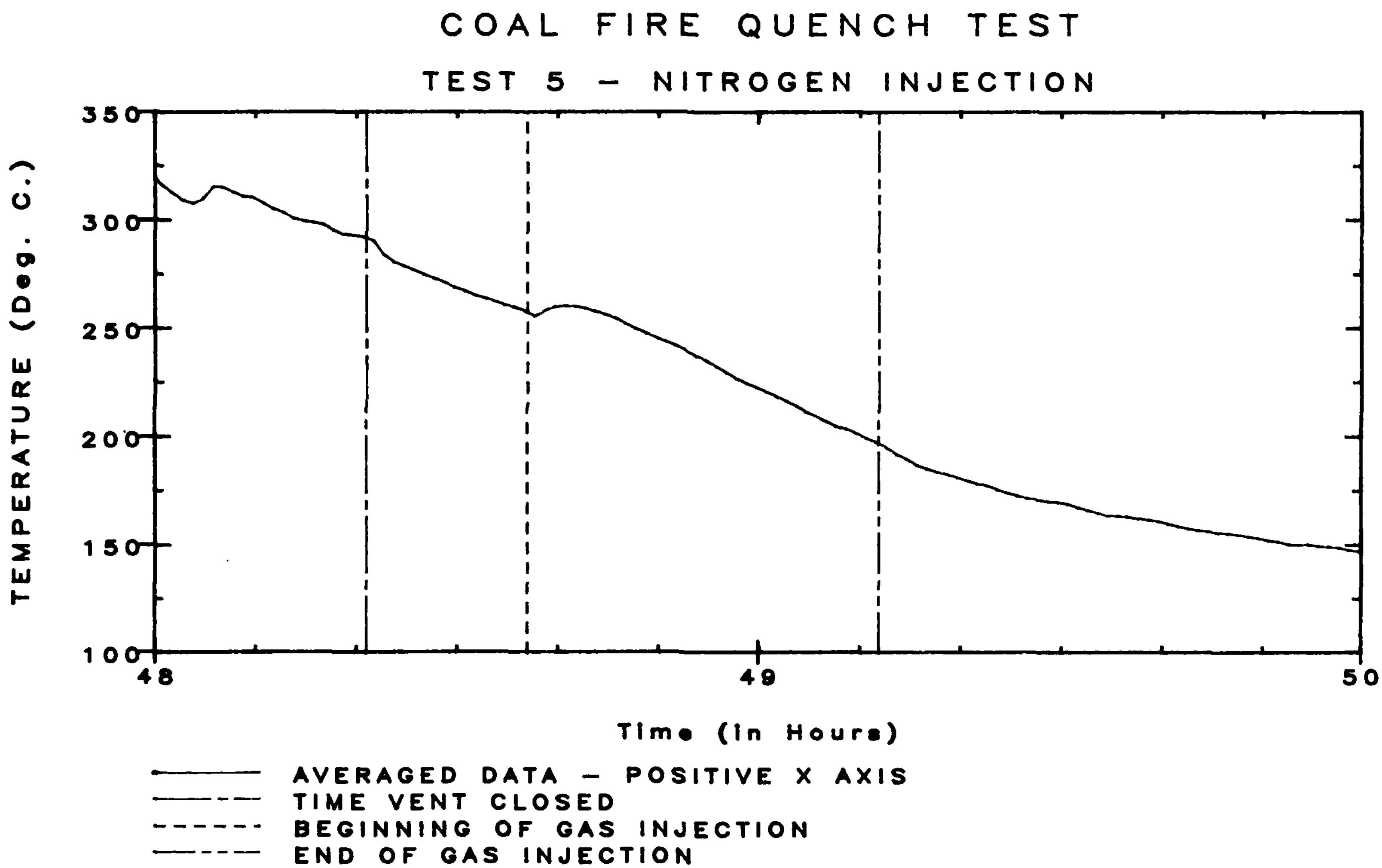


FIGURE 4-5. HOT FIRE QUENCH TEST WITH NITROGEN INJECTION - TEMPERATURE HISTORY

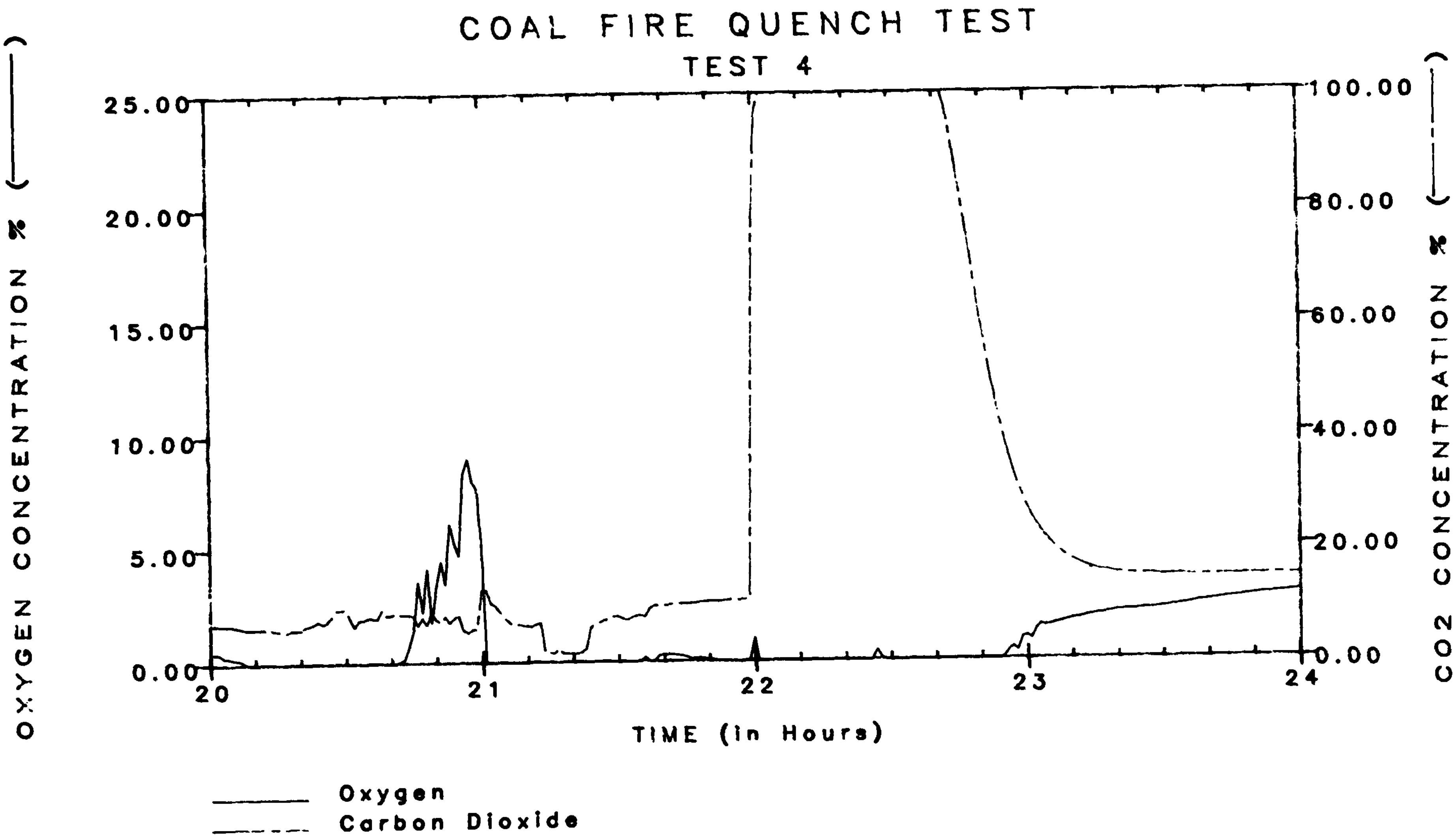


FIGURE 4-6. HOT FIRE QUENCH TEST WITH CARBON DIOXIDE INJECTION - OXYGEN AND CARBON DIOXIDE CONCENTRATIONS

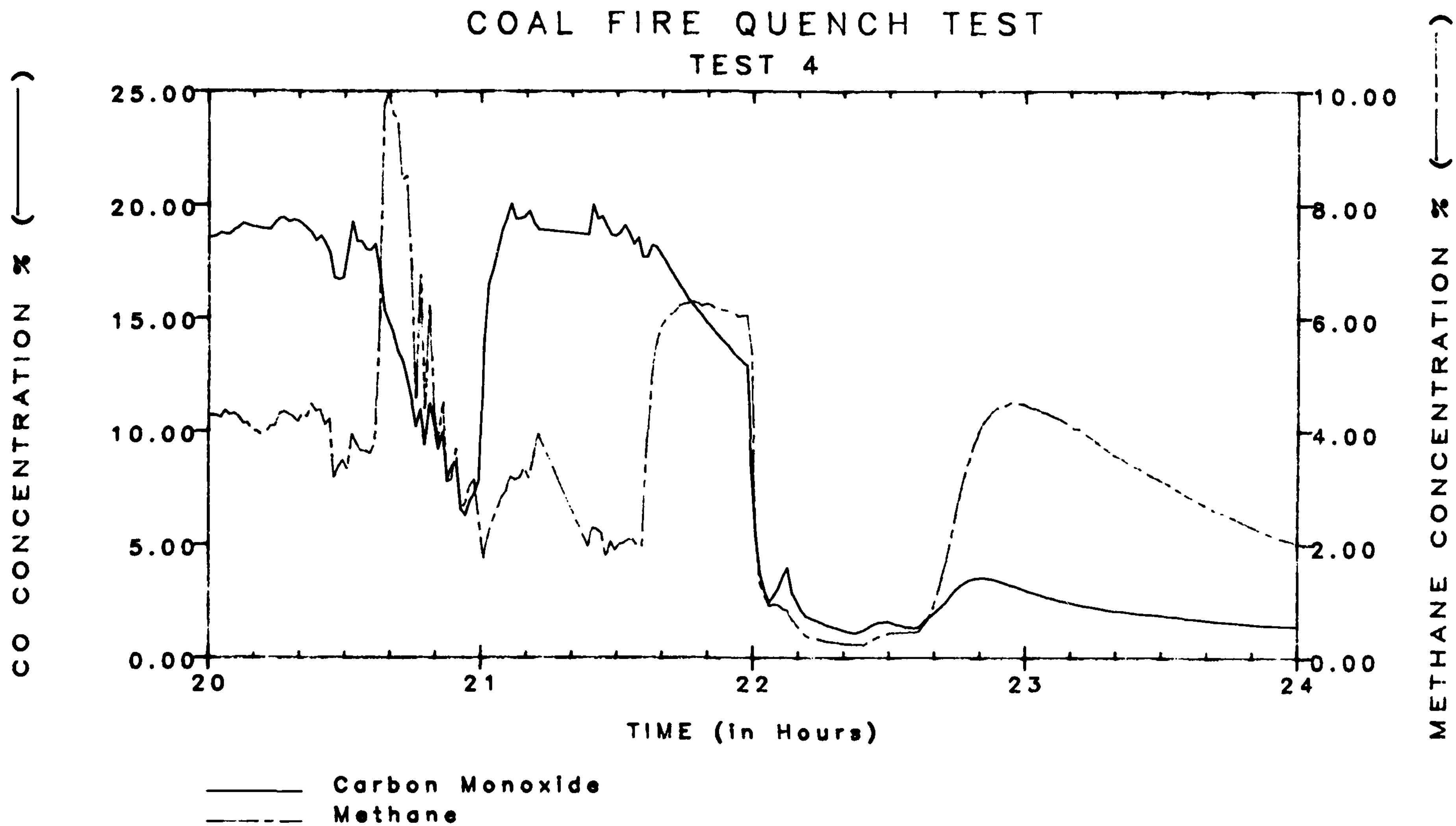


FIGURE 4-7. HOT FIRE QUENCH TEST WITH CARBON DIOXIDE INJECTION - CARBON MONOXIDE AND METHANE CONCENTRATIONS

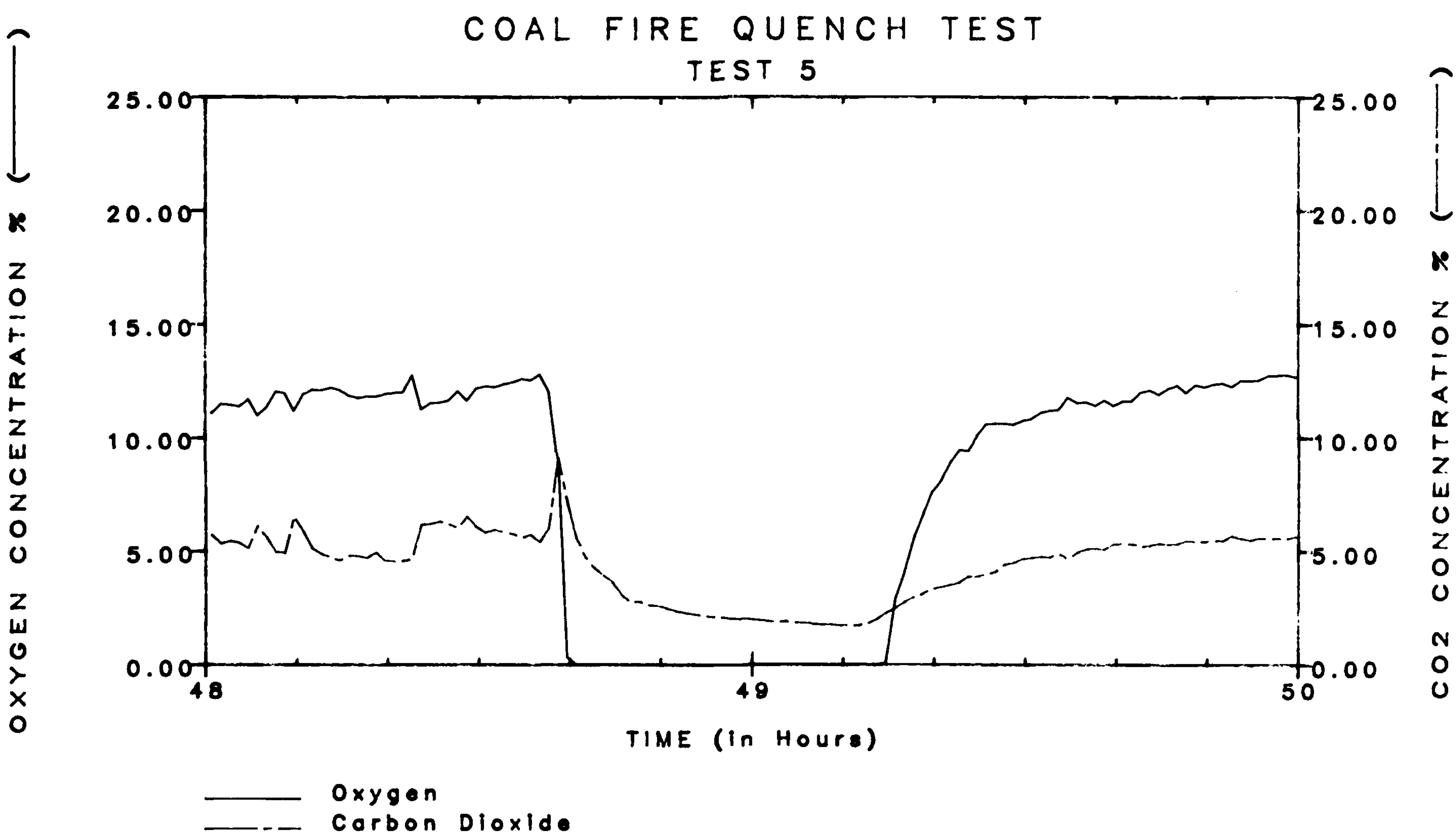


FIGURE 4-8. HOT FIRE QUENCH TEST WITH NITROGEN INJECTION - OXYGEN AND CARBON DIOXIDE CONCENTRATIONS

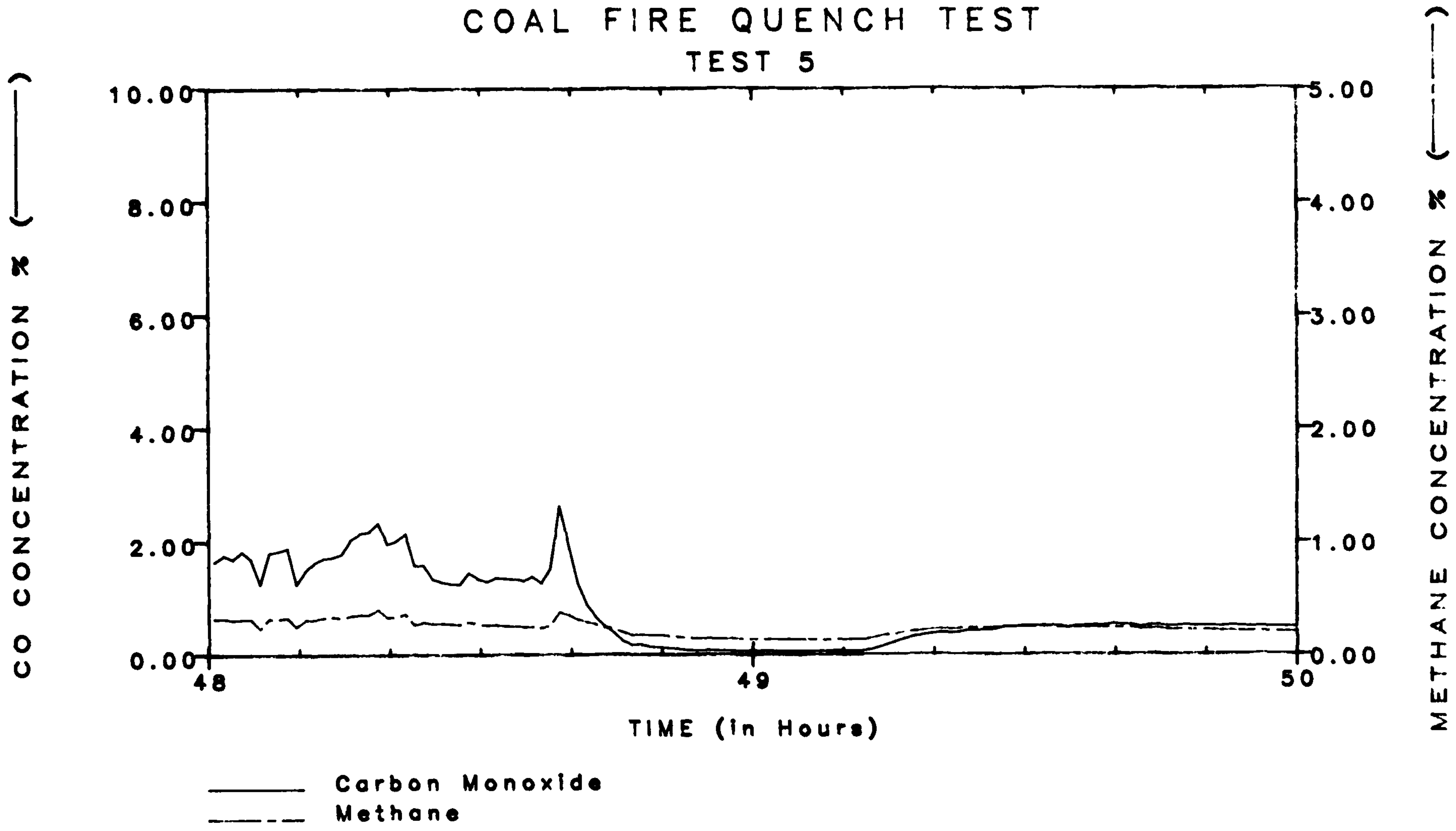


FIGURE 4-9. HOT FIRE QUENCH TEST WITH NITROGEN INJECTION - CARBON MONOXIDE AND METHANE CONCENTRATIONS

5.0 COAL COLUMN EXTINGUISHMENT TESTS

The methodology for the coal column extinguishment tests was based on results obtained from the permeation and fire quench tests. The permeation tests indicated that the most effective gas permeation was accomplished by injecting nitrogen, at a high rate of flow, into the middle of the coal column. The fire quench tests supported these results, demonstrating that nitrogen injected in this manner effectively extinguished a small-scale fire. The coal column tests were the final phase of this project.

5.1 Objectives

The tests were designed to determine permeation and gas retention times for carbon dioxide and nitrogen in deep-seated fire conditions. The behavior of these two gases in a deep-seated fire condition were not known, although testing in the absence of fire seemed to indicate that nitrogen was superior to carbon dioxide as an extinguishing agent. Specific objectives were:

a. To evaluate the method developed in the fire quench tests by establishing a deep-seated coal fire in a column of coal and

b. To evaluate the effectiveness of carbon dioxide and nitrogen when applied to this deep-seated fire.

5.2 Fire Test Scenario

The tests were conducted aboard the MAYO LYKES, in the converted escape trunk previously used in the permeation studies (See Section 3.3 for description of the converted escape trunk). The tests simulated a deep-seated coal fire in a cargo hold. A fan and air compressor provided forced ventilation. The ignition source was a series of electrical resistance heaters located between probes 4 and 5. Once a fire was determined to be deep-seated, one of the extinguishing agents (carbon dioxide or nitrogen) was applied at a high flow rate. The retention time of each gas was observed. When the inerting gas dissipated and there was sufficient oxygen in the chamber to support combustion, the coal fire resumed.

Gases were injected at a high flow rate, since the permeation studies showed low flow to be ineffective. Gases were injected into the top or the middle of the coal column, also a result of information acquired during the permeation tests.

The heat ball from the permeation test was replaced with electrical resistance heaters. As the resistance heaters had a tendency to burn out, it was necessary to install several heaters in the trunk, thus creating a "fire zone."

An air supply system was added to ventilate the fire and help it become established. The column was purged of inerting gas after each test via an air compressor (50 psi, 200 cubic feet/hour delivery). After the air purge, the column was readied for another test with a different extinguishing agent.

5.3 Test Procedures

Testing commenced after 5 minutes of background scanning by the data acquisition system. The 5-minute scan time was used to establish baseline for each instrument.

The following sequence of events was observed:

a. The resistance heaters were placed between probes 4 and 5.

b. The data acquisition system was started.

c. The forced ventilation system was activated to supply the fire with sufficient oxygen.

d. The extinguishing agent (carbon dioxide or nitrogen) was applied at a discharge rate of 100 cubic feet/hour.

e. Forced ventilation was secured.

f. Dissipation of the extinguishing agent was observed.

g. The air compressor was started to force volatile gases out.

h. The procedure was repeated with the next extinguishing agent.

The principal safety hazard was the build-up of methane gas and volatile vapors which are emitted from coal. To avoid such a risk oxygen, volatile gases (methane), and carbon dioxide build-up were continuously monitored in the vicinity of the test chamber. A methane gas analyzer and a hydrocarbon analyzer continually sampled the atmosphere in the coal column and in the space directly above the coal. If the methane concentration reached 3 percent or the hydrocarbon analyzer reached 50 percent of the lower explosive limit, an audible alarm sounded. Self-contained breathing apparatus was provided to individuals actually involved in testing.

5.4 Data Analysis and Test Results

Gas measurements were obtained by the same method that was used in the permeation studies. There were five levels of probes. Each probe had three chambers from which gas samples could be drawn. Gas samples were drawn at specified times. These times were close together at the beginning of the test and were further spaced as time passed. The general test arrangement including instrumentation, gas injection points, heaters and ventillation in the coal column appears in Figure 5-1.

5.4.1 Top vs Side Injection

Figure 5-2 (A through E) compares top injection and side injection for carbon dioxide at the different levels. The carbon dioxide was injected for the first 60 minutes of each test. The graphs begin at the time of gas injection. The most notable observation with all the graphs is the fact that the initial concentration of oxygen at each level is below the level needed to support rapid combustion. Another important observation is that regardless of whether the injection was from the top or side the general shape of the curve was similar for each particular level. The differences in the curves appear to be in the arrival time of the injected gas. For example the sequence of graphs in Figure 5-2 illustrates the sinking effect of carbon dioxide which displaces oxygen as it sinks to the bottom of the column. Not only was the side injection more effective by providing faster response at the lower levels, but Figure 5-E shows it was also more effective at the higher levels. Figure 5-E shows that the top injection caused the oxygen level to drop more at minute 20, but by minute 60 the concentration of oxygen from the top injection was approximately 17 percent while the concentration of oxygen from the side injection was approximately 3 percent. The drop in the curve of the top injection that starts around minute 150 is attributed to smoldering of the coal which in turn used up the oxygen. This same phenomenon occurred with the side injection when the oxygen level reached a concentration that could support combustion. On the graph this occurred at minute 200 and decreased until minute 300. Figures 5-2, D and E show how quickly the oxygen returns to the upper levels of the column. Figures 5-2, A through C show that the oxygen level returns gradually in the lower portion of the coal column. In the case of the lowest two levels, the oxygen concentration never rises to a level that would support rapid combustion.

Figure 5-3 averages the methane concentrations for top injection and for side injection of carbon dioxide. The graph shows that up to about minute 300 the side injection is more effective in reducing the methane concentration.

Levels 1 and 2 showed substantially greater concentrations of carbon dioxide from side injection than from top injection as shown in Figure 5-4 A through D. The concentration difference between top injection and side

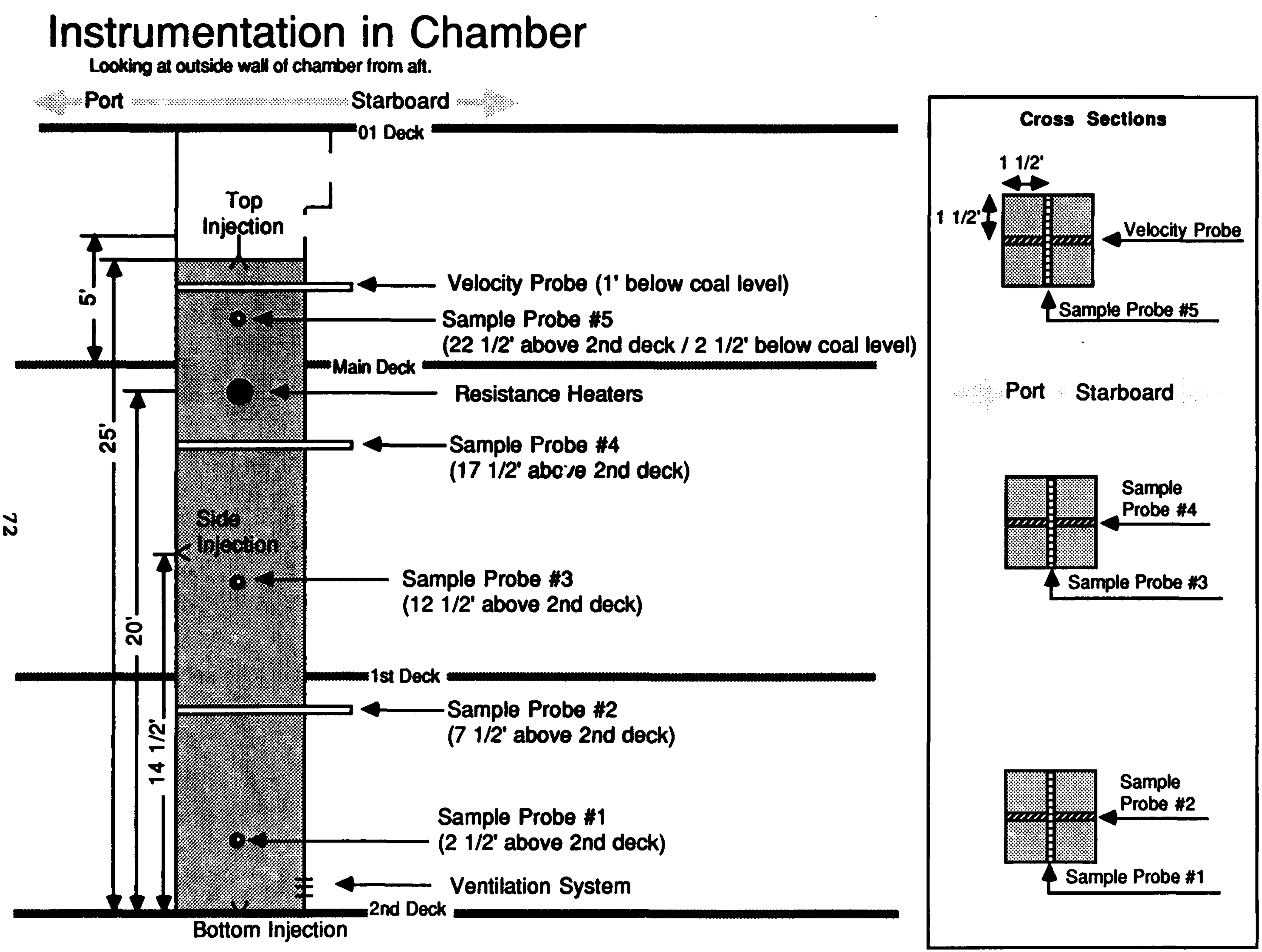


FIGURE 5-1. ARRANGEMENT OF COAL COLUMN EXTINGUISHMENT TESTS

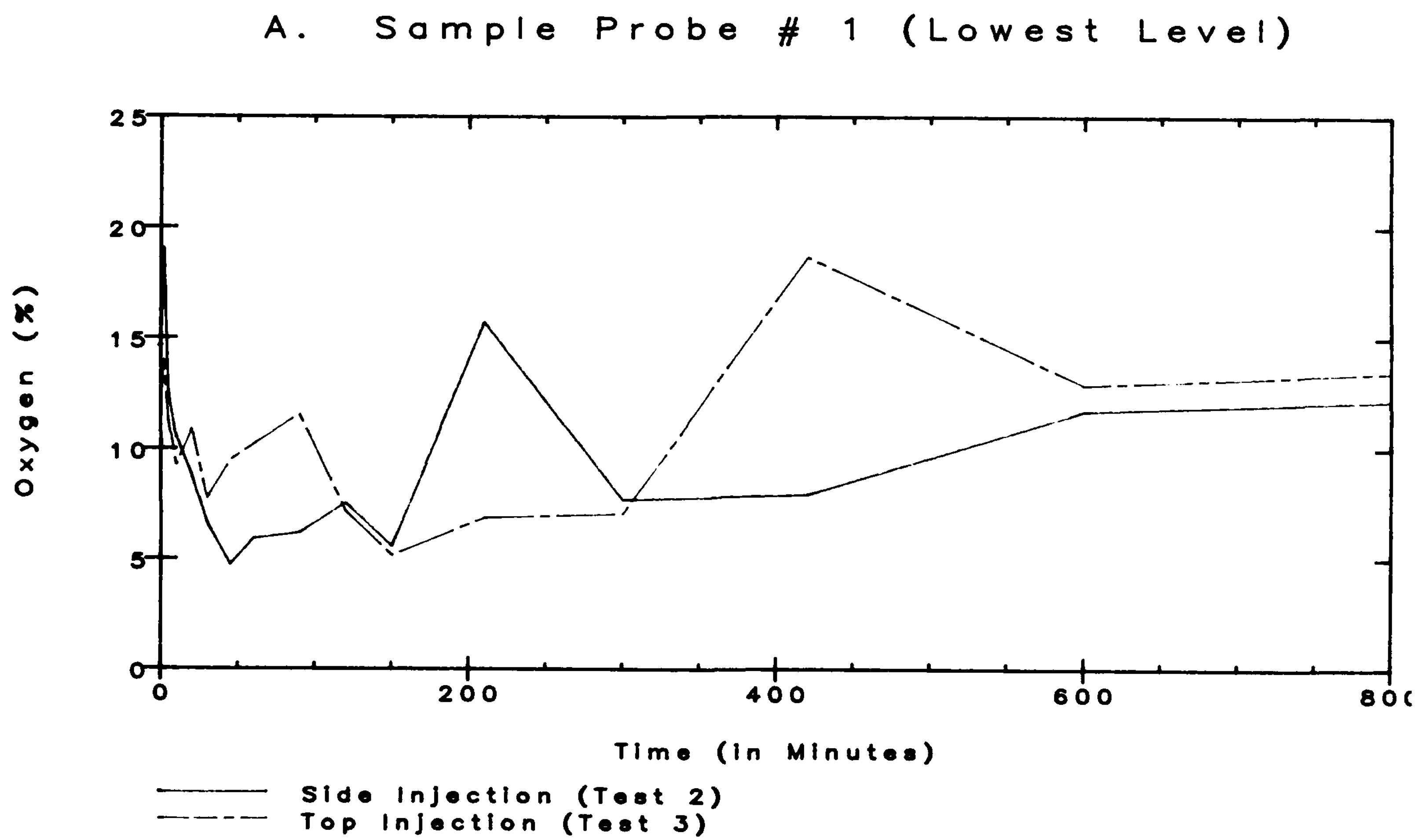


FIGURE 5-2A. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - OXYGEN CONCENTRATION - LOWEST LEVEL

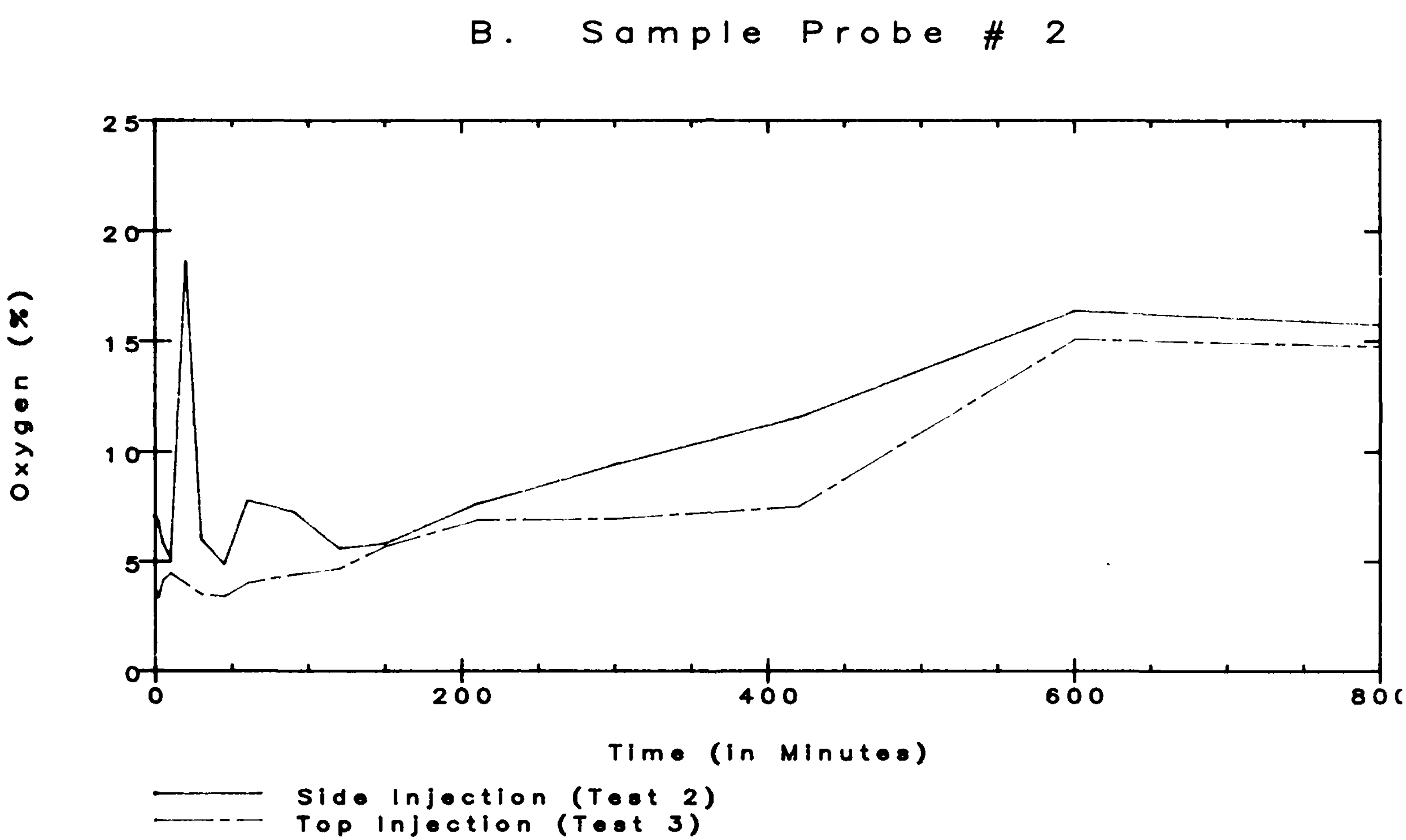


FIGURE 5-2B. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - OXYGEN CONCENTRATION

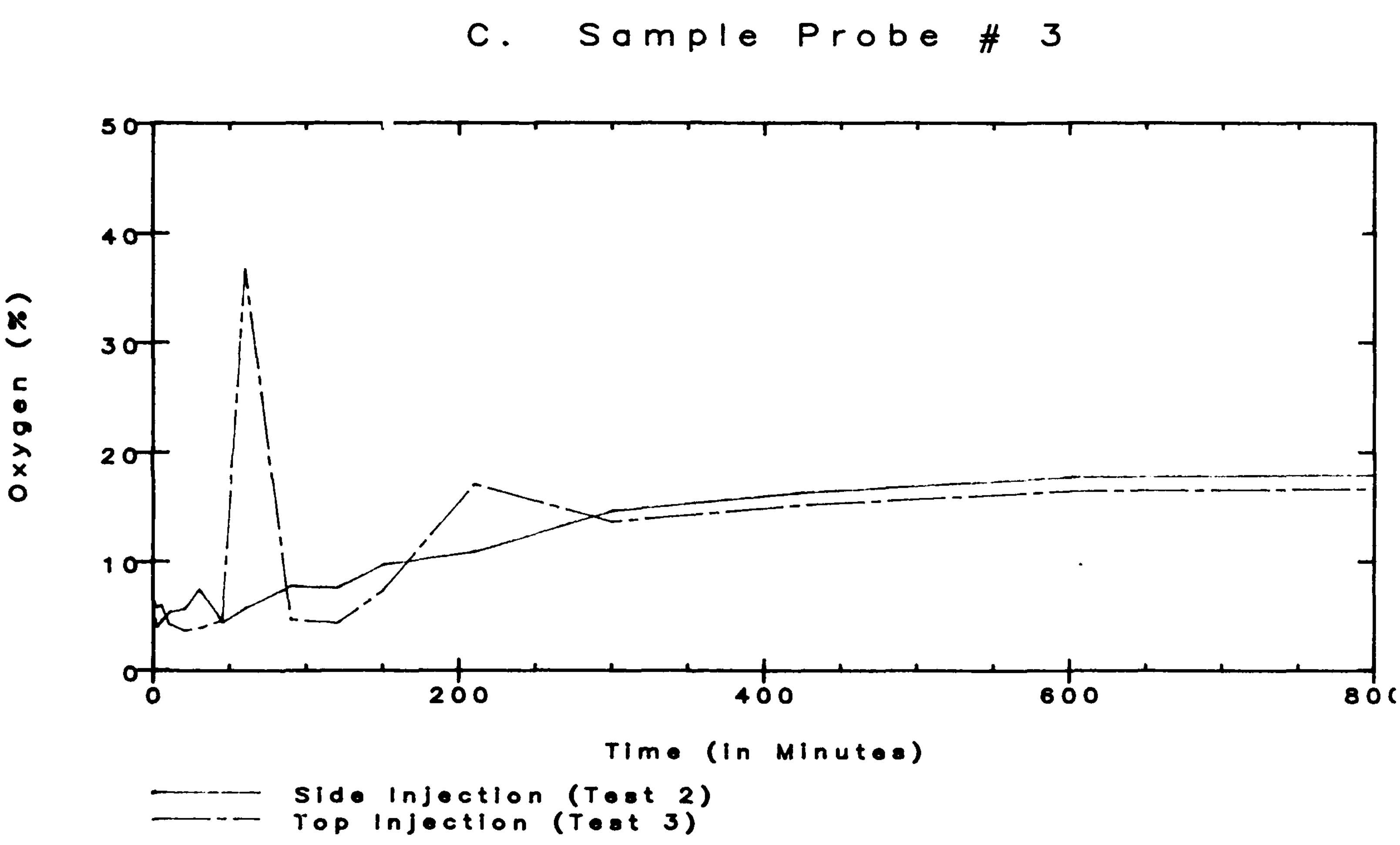


FIGURE 5-2C. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - OXYGEN CONCENTRATION

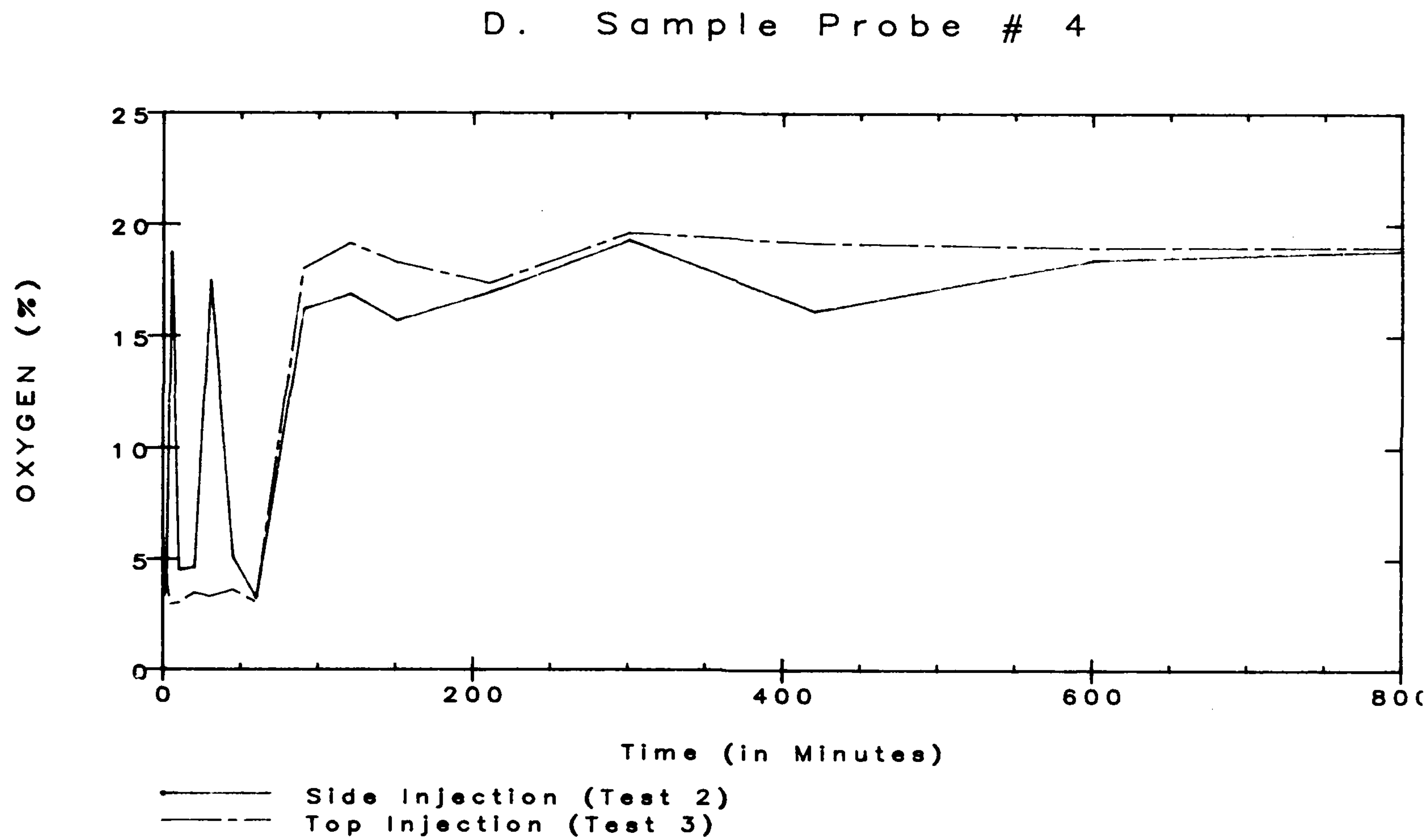


FIGURE 5-2D. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - OXYGEN CONCENTRATION

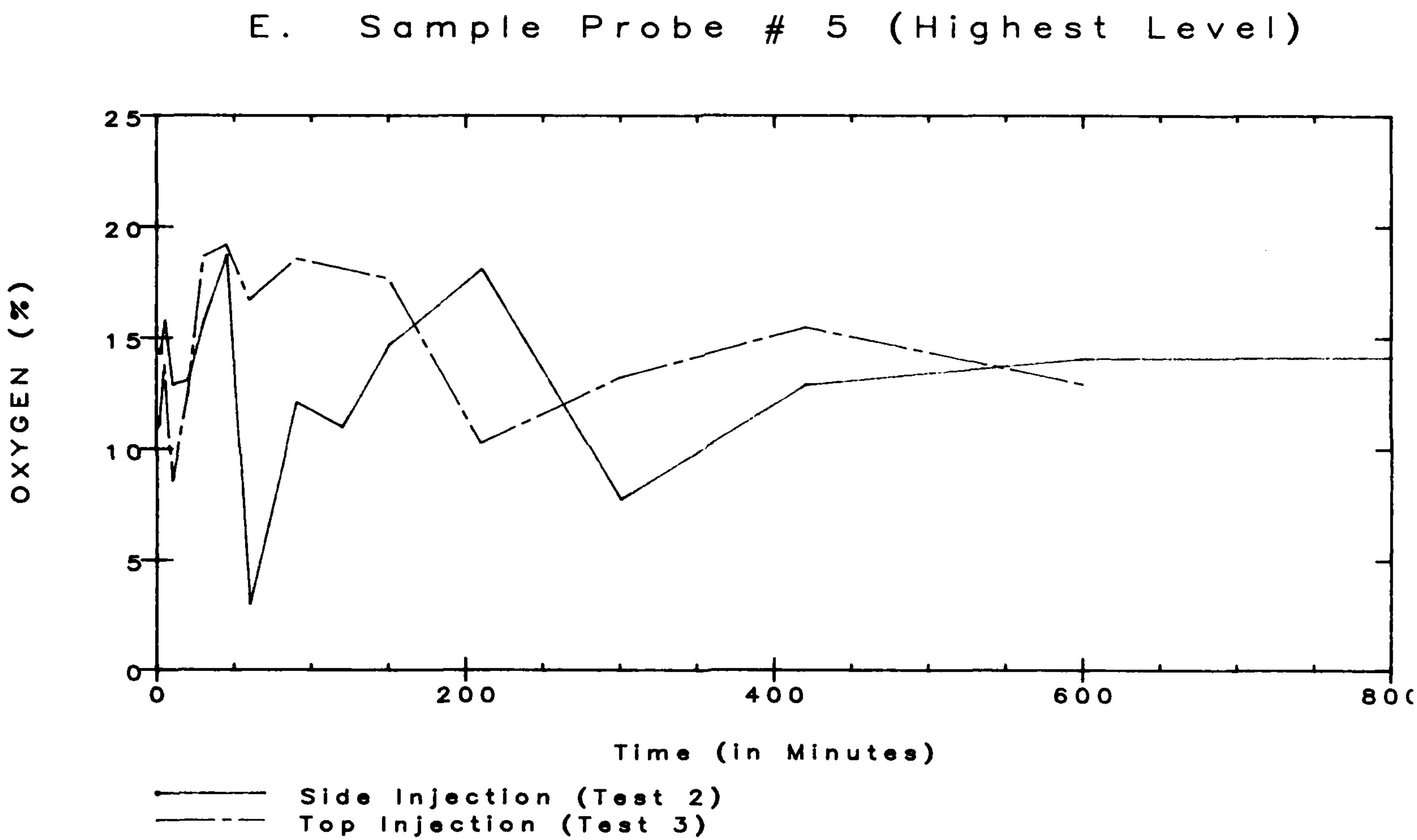


FIGURE 5-2E. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - OXYGEN CONCENTRATION

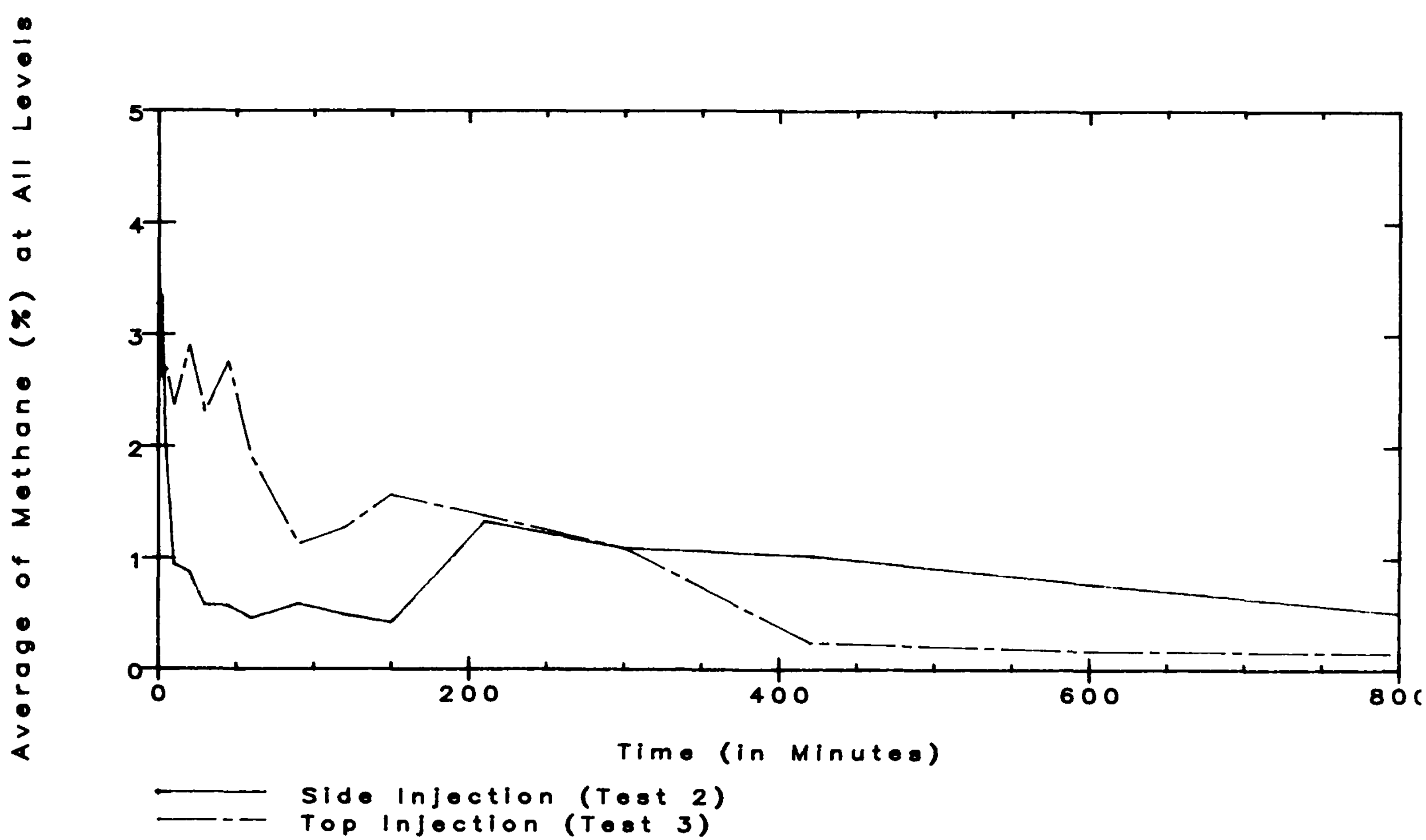


FIGURE 5-3. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - AVERAGE METHANE CONCENTRATION

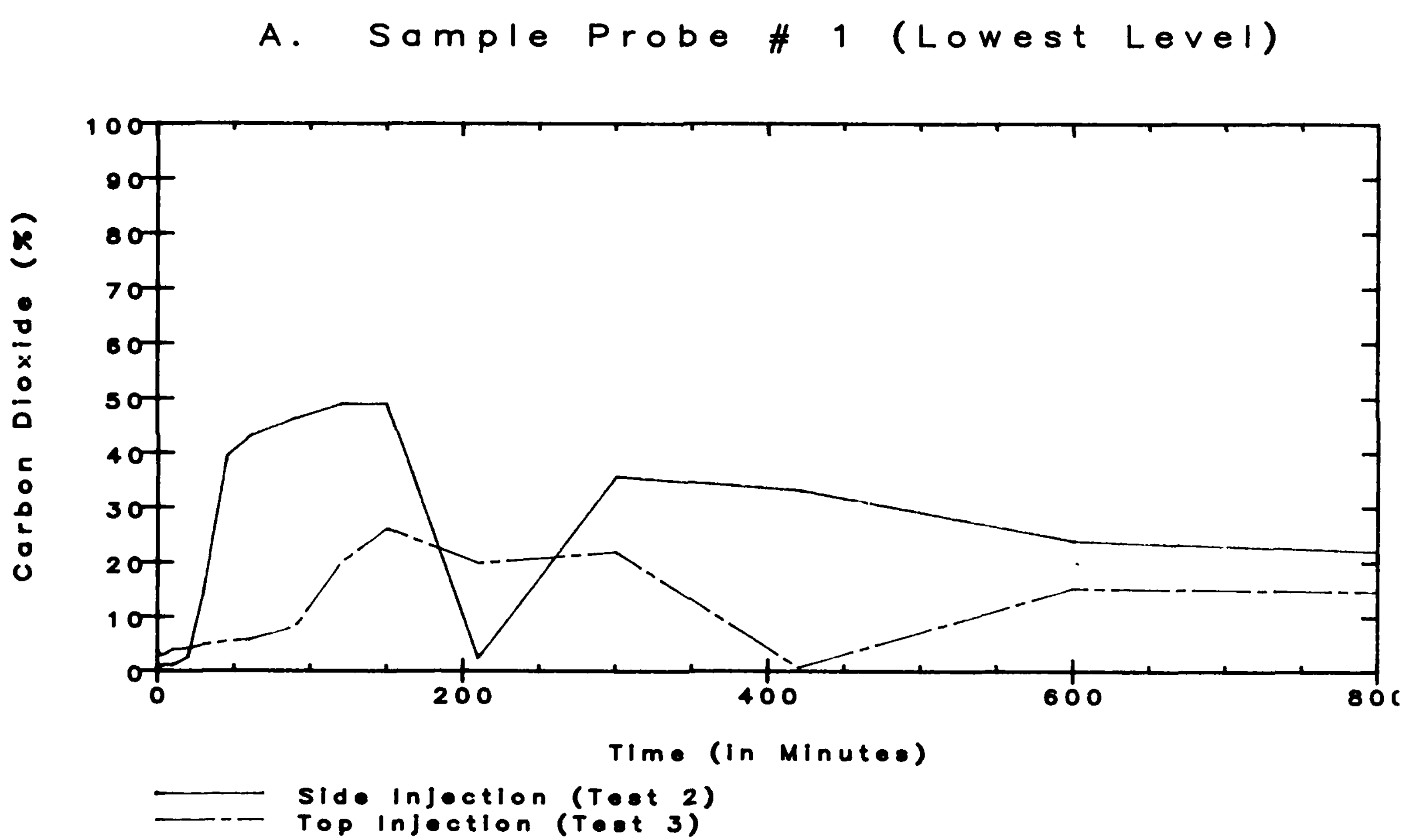


FIGURE 5-4A. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - CARBON DIOXIDE CONCENTRATIONS -LOWEST LEVEL

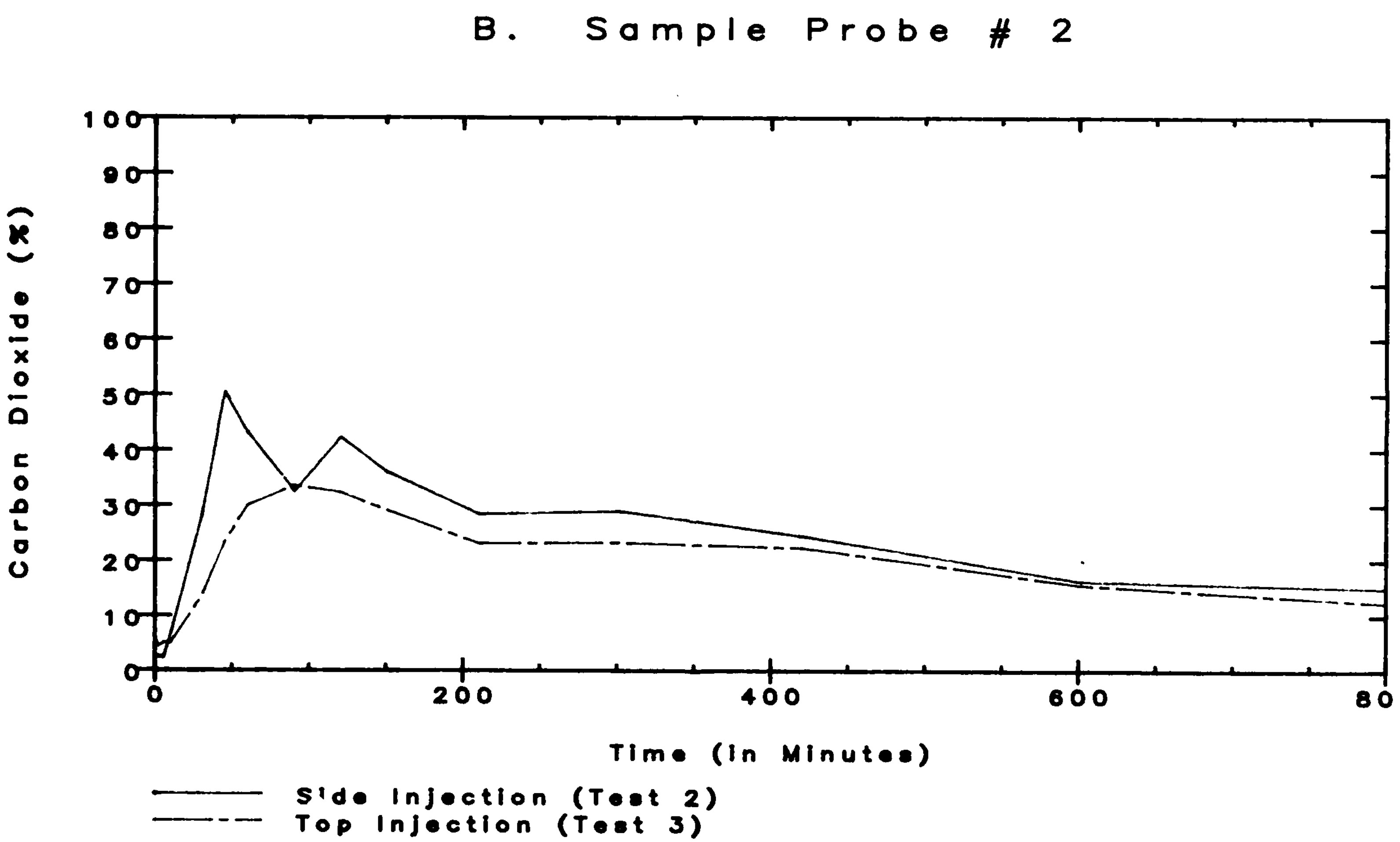


FIGURE 5-4B. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - CARBON DIOXIDE CONCENTRATIONS

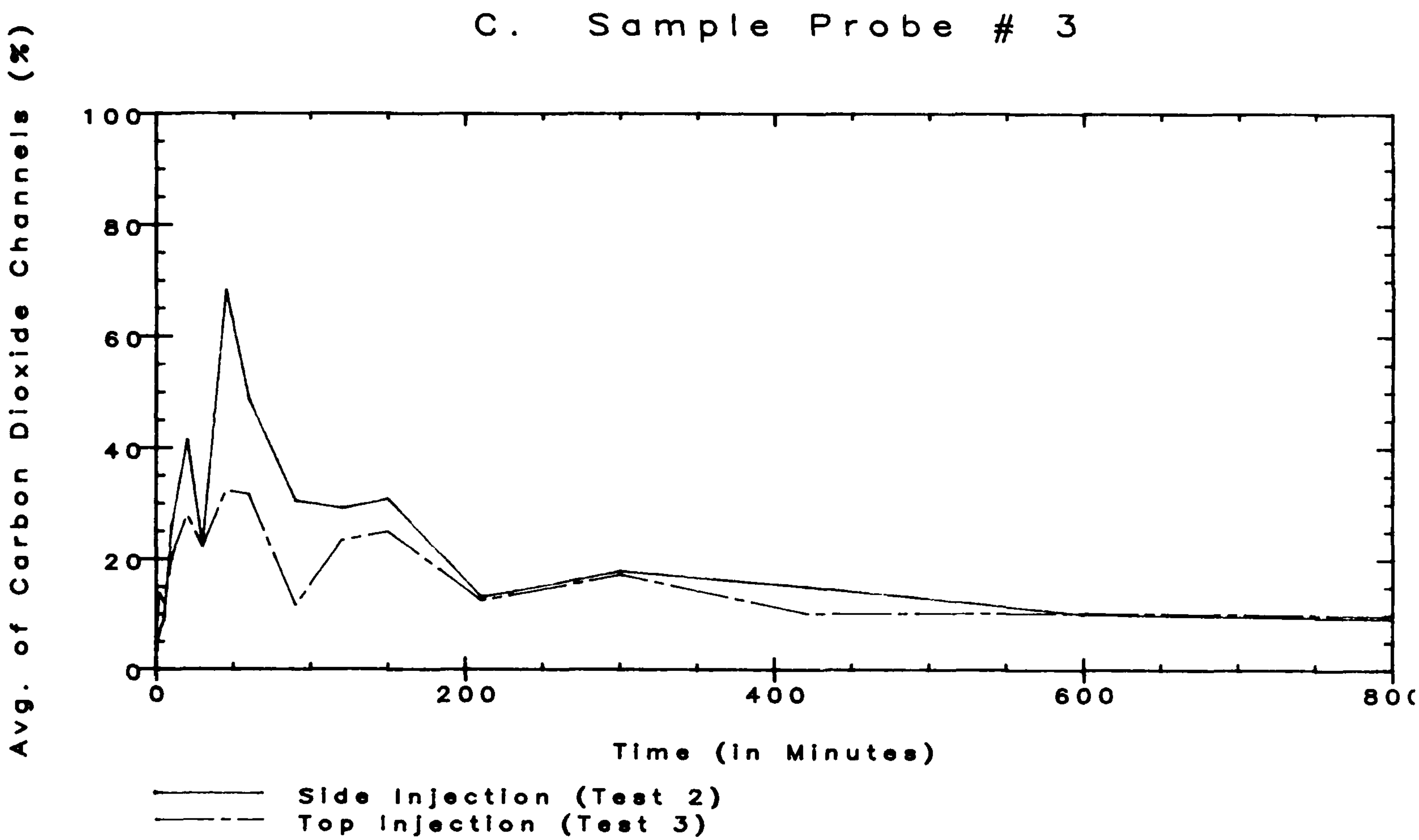


FIGURE 5-4C. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - CARBON DIOXIDE CONCENTRATIONS

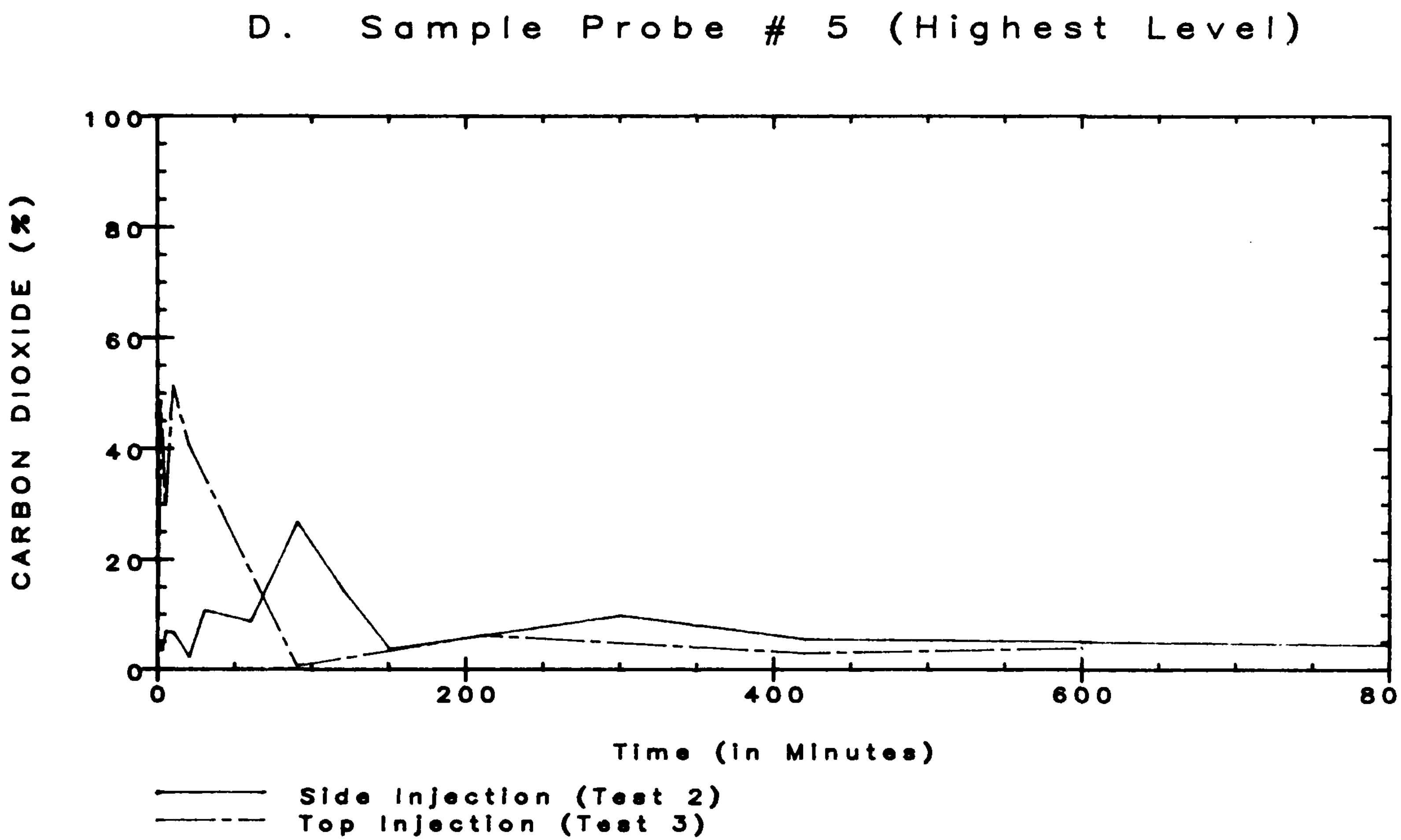


FIGURE 5-4D. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - CARBON DIOXIDE CONCENTRATIONS -HIGHEST LEVEL

injection observed in Figure 5-4C is not surprising since the probe at level 3 was 2 feet below the side injection nozzle. However, it is interesting to note that in the upper part of the column the initial concentration from top injection is much higher than from side injection but then falls off fast and is essentially zero before the concentration of carbon dioxide from the side injection reaches its maximum (see Figure 5-4D).

Figure 5-5 averages the carbon dioxide concentrations from all five sample probes (i.e., from all levels) for top injection and for side injection of carbon dioxide. The graph shows that the side injection created a much higher concentration of carbon dioxide than the top injection. The more carbon dioxide that remains in the column, the more effective it is. All of these graphs show that the side injection is much more effective than top injection.

5.4.2 <u>Carbon Dioxide vs Nitrogen Injection</u>

A side injection carbon dioxide test was compared with a side injection nitrogen test to evaluate the relative effectiveness of the two gasses. To obtain the overall effectiveness of each gas, the average concentration of oxygen from all five sample probes (i.e., from all levels) was compared for the carbon dioxide injection and the nitrogen injection. The results are displayed in Figure 5-6. This figure indicates that nitrogen is more effective than carbon dioxide. The oxygen concentration for the nitrogen injection remained between 10 and 11 percent for up to 800 minutes. The oxygen level for the carbon dioxide injection rose above 12.5 percent at around 250 minutes. This oxygen concentration is sufficient to support smoldering. This corroborates the longer retention times observed for nitrogen in the permeation studies.

Results from the individual levels illustrate where each gas is more effective (see Figure 5-7A through E). The graph for sample probe #5 shows that nitrogen keeps the oxygen concentration lower than carbon dioxide throughout most of the test and only at the end of the test does the oxygen level return to a concentration that could cause smoldering. This is more clearly illustrated at the next level down, sample probe #4. With the carbon dioxide injection, the oxygen concentration returns to 16 percent by minute 100 and remains at or above that concentration for the remainder of the test. The oxygen concentration with the nitrogen injection does not reach more than 12 percent from minute 175 until the end of the test. The same phenomenon is dramatically shown for sample probe #3. Test 1, where nitrogen was injected, shows an oxygen concentration drop from about 15 percent to below 3 percent with a return to less than 14 percent in over 800 minutes. The test where carbon dioxide was injected shows an initial concentration of about 5 percent, with a rise to about 18 percent oxygen concentration, in about 600 minutes. Nitrogen is clearly the more effective agent in the upper half of the column.

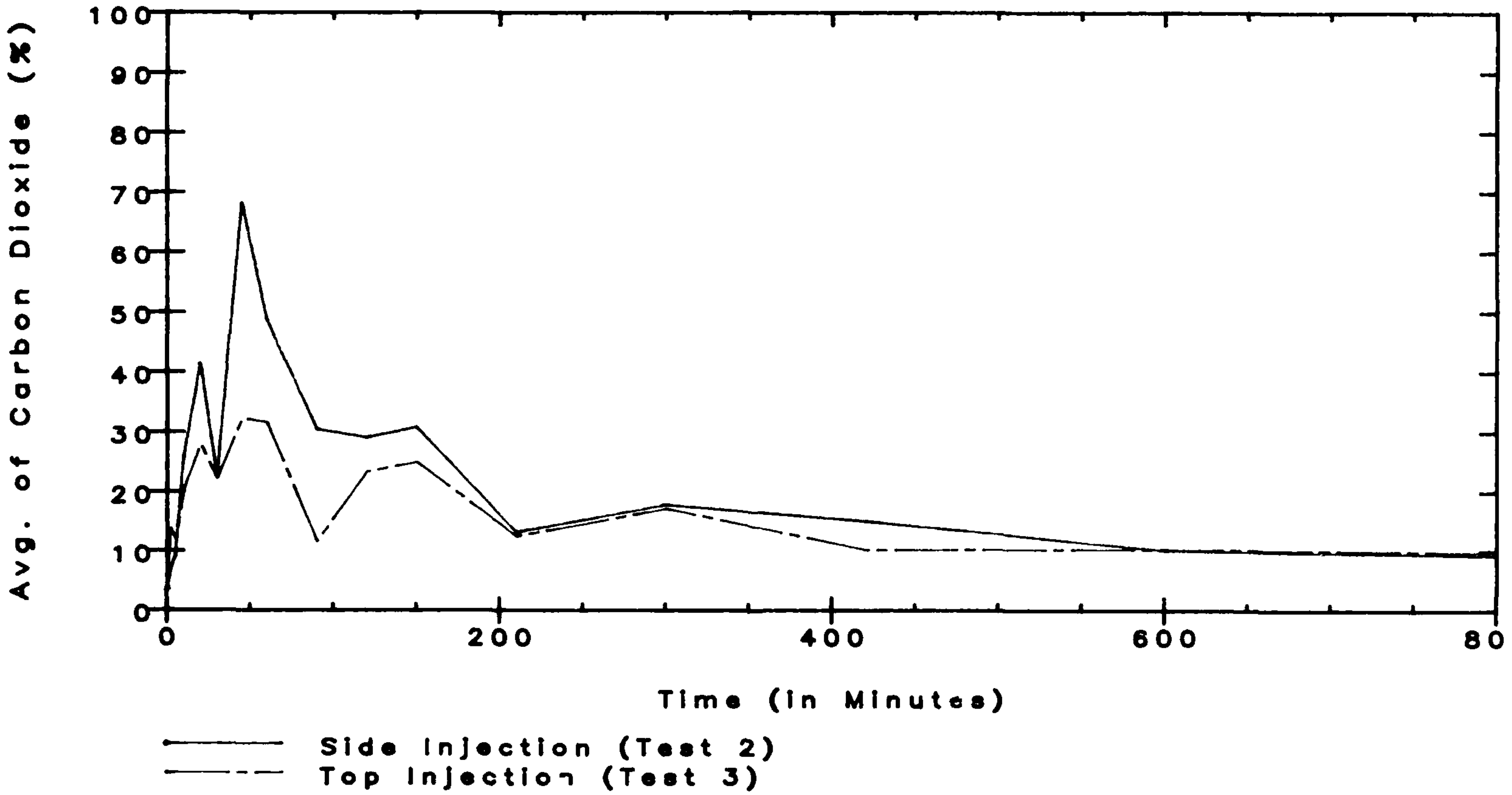


FIGURE 5-5. COAL COLUMN FIRE EXTINGUISHMENT - TOP vs SIDE INJECTION OF CARBON DIOXIDE - AVERAGE CARBON DIOXIDE CONCENTRATION

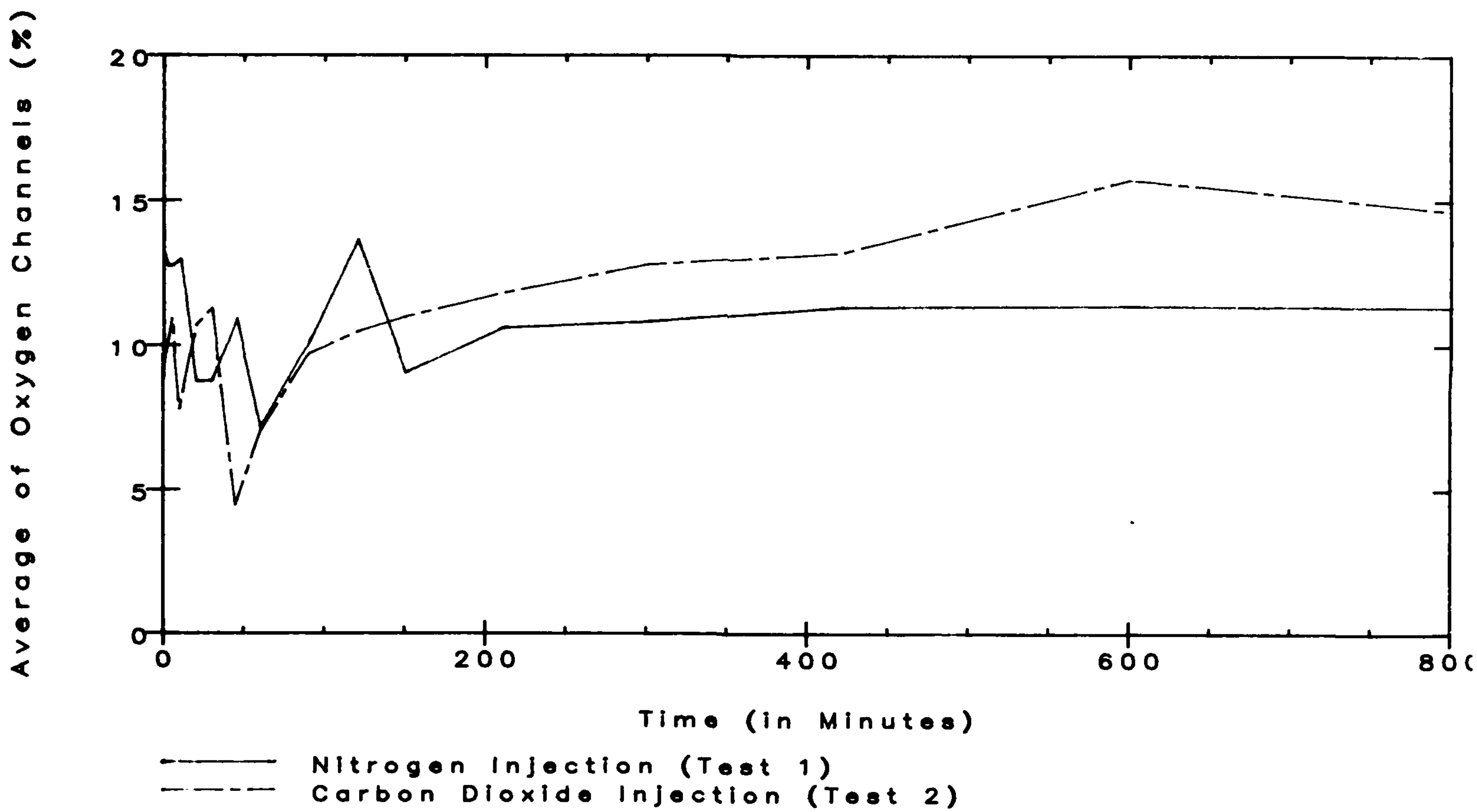


FIGURE 5-6. COAL COLUMN FIRE EXTINGUISHMENT - CARBON DIOXIDE vs NITROGEN INJECTION (FROM SIDE) - AVERAGE OXYGEN CONCENTRATION

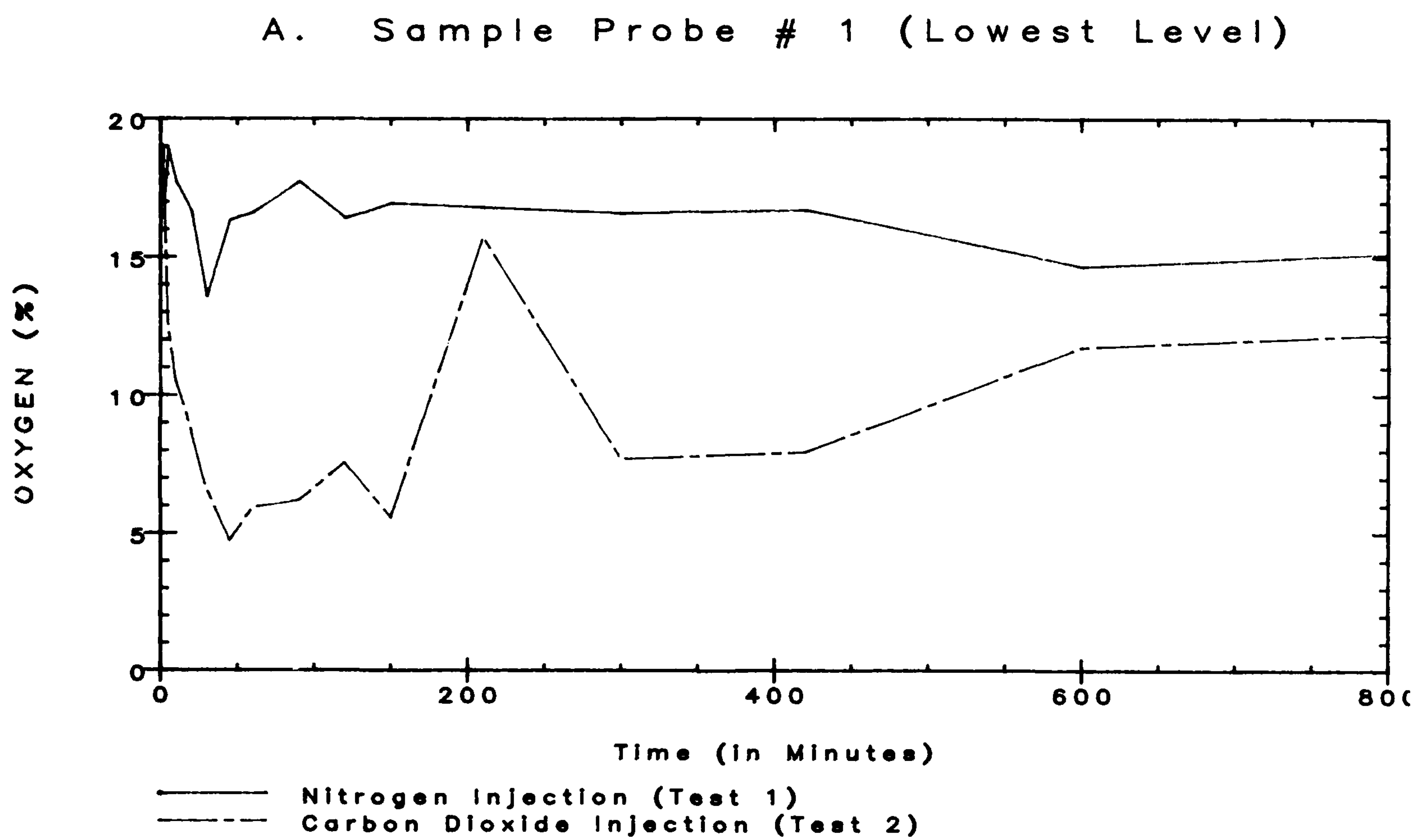


FIGURE 5-7A. COAL COLUMN FIRE EXTINGUISHMENT - CARBON DIOXIDE vs NITROGEN INJECTION (FROM SIDE) - OXYGEN CONCENTRATION - LOWEST LEVEL

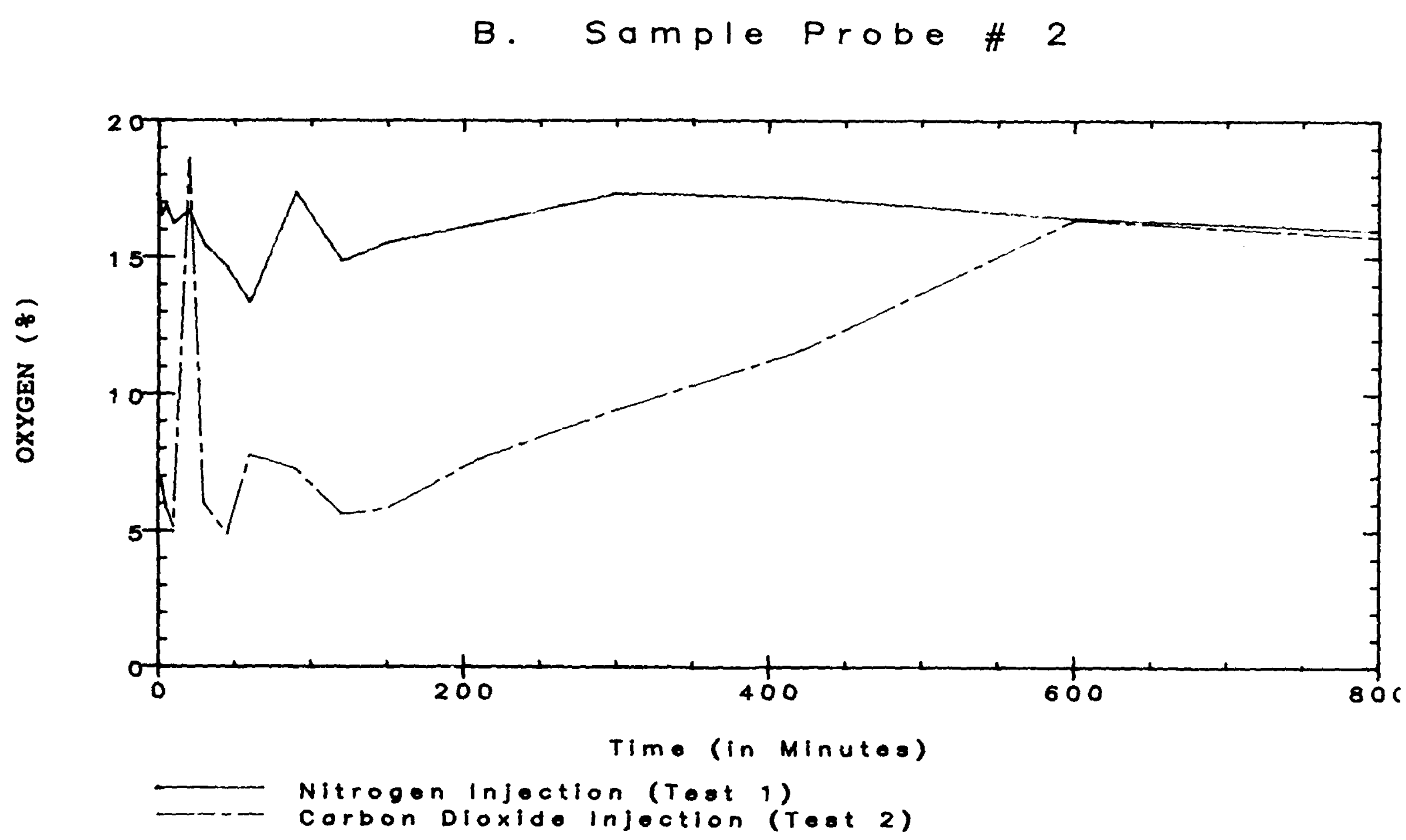


FIGURE 5-7B. COAL COLUMN FIRE EXTINGUISHMENT - CARBON DIOXIDE vs NITROGEN INJECTION (FROM SIDE) - OXYGEN CONCENTRATION

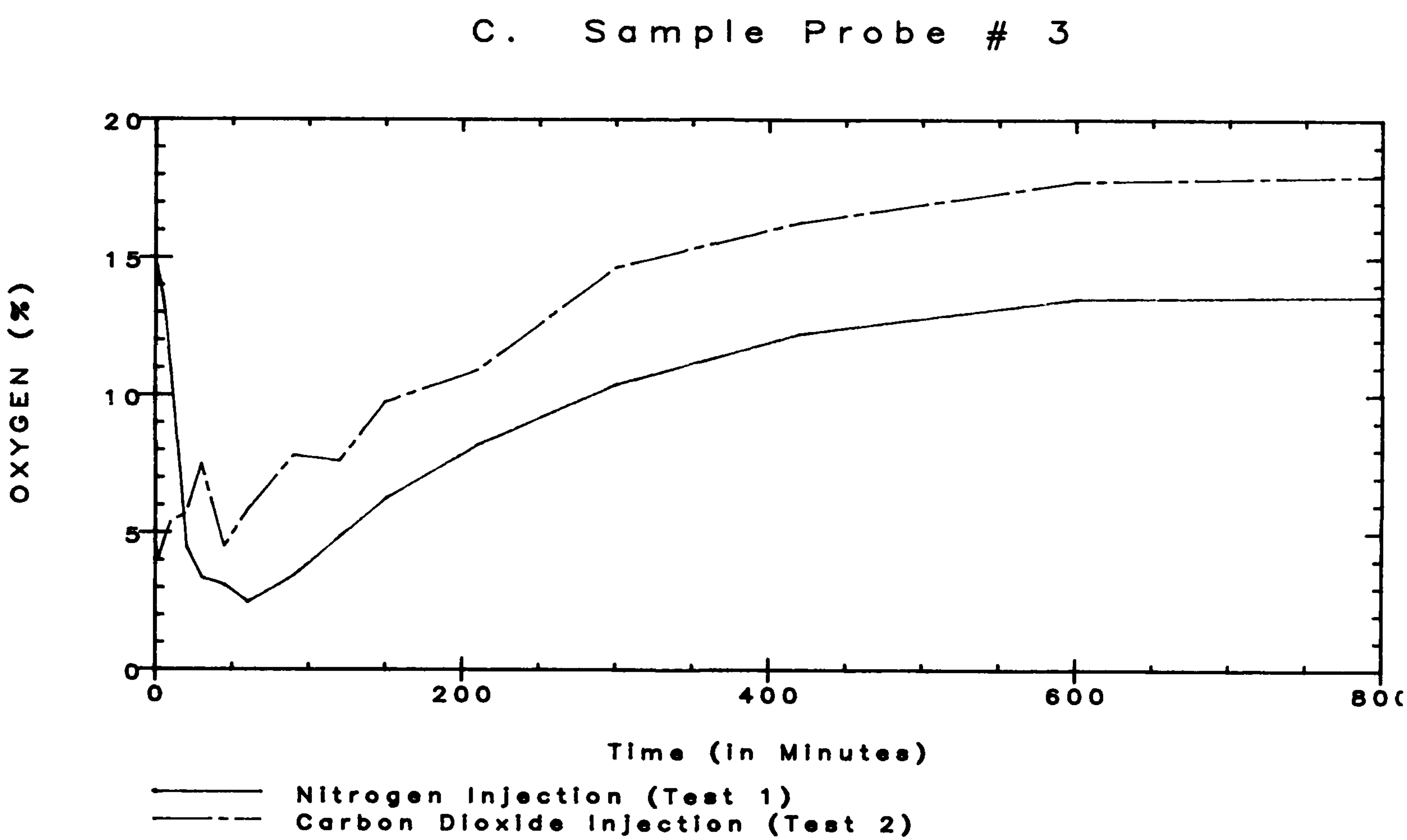


FIGURE 5-7C. COAL COLUMN FIRE EXTINGUISHMENT - CARBON DIOXIDE vs NITROGEN INJECTION (FROM SIDE) - OXYGEN CONCENTRATION

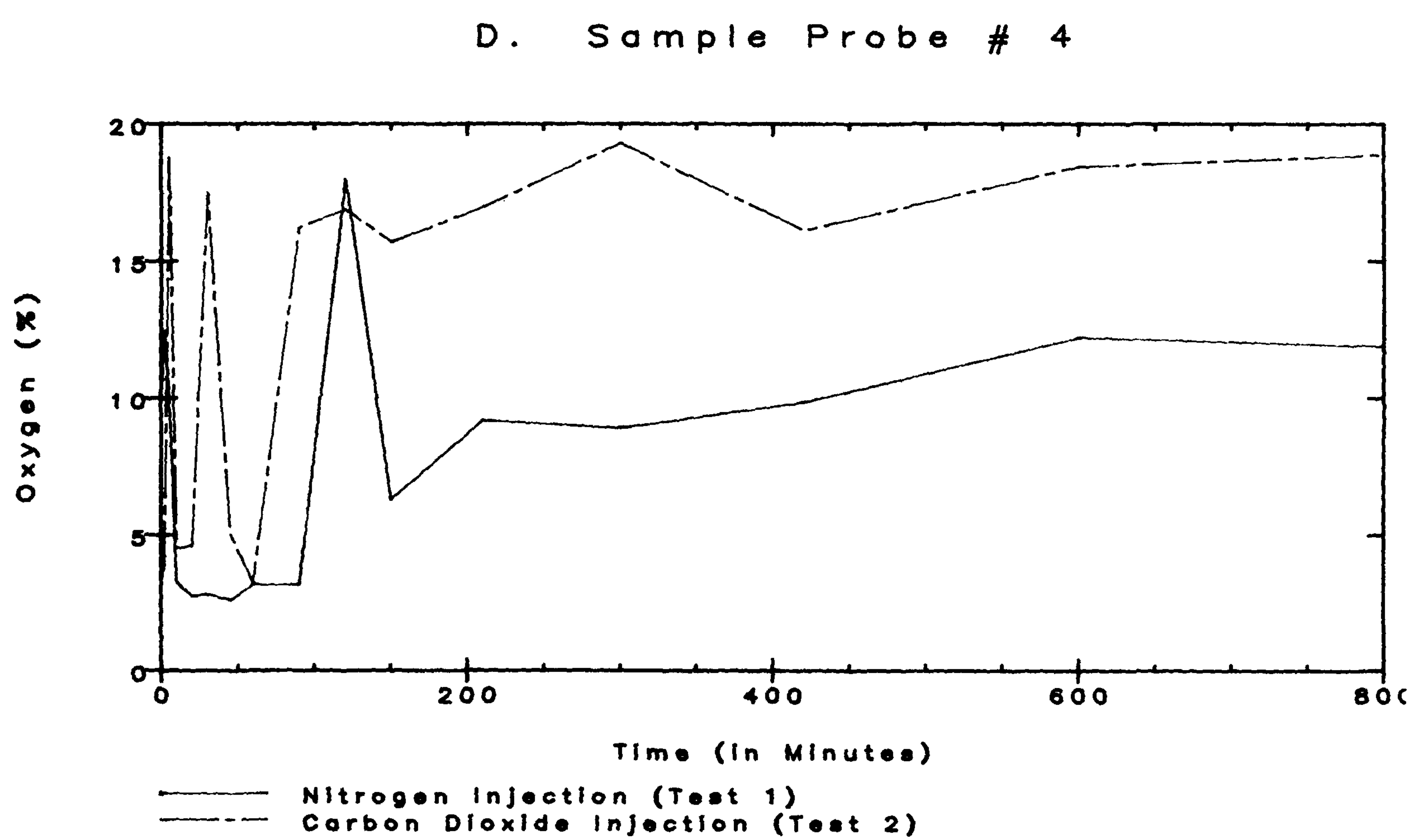


FIGURE 5-7D. COAL COLUMN FIRE EXTINGUISHMENT - CARBON DIOXIDE vs NITROGEN INJECTION (FROM SIDE) - OXYGEN CONCENTRATION

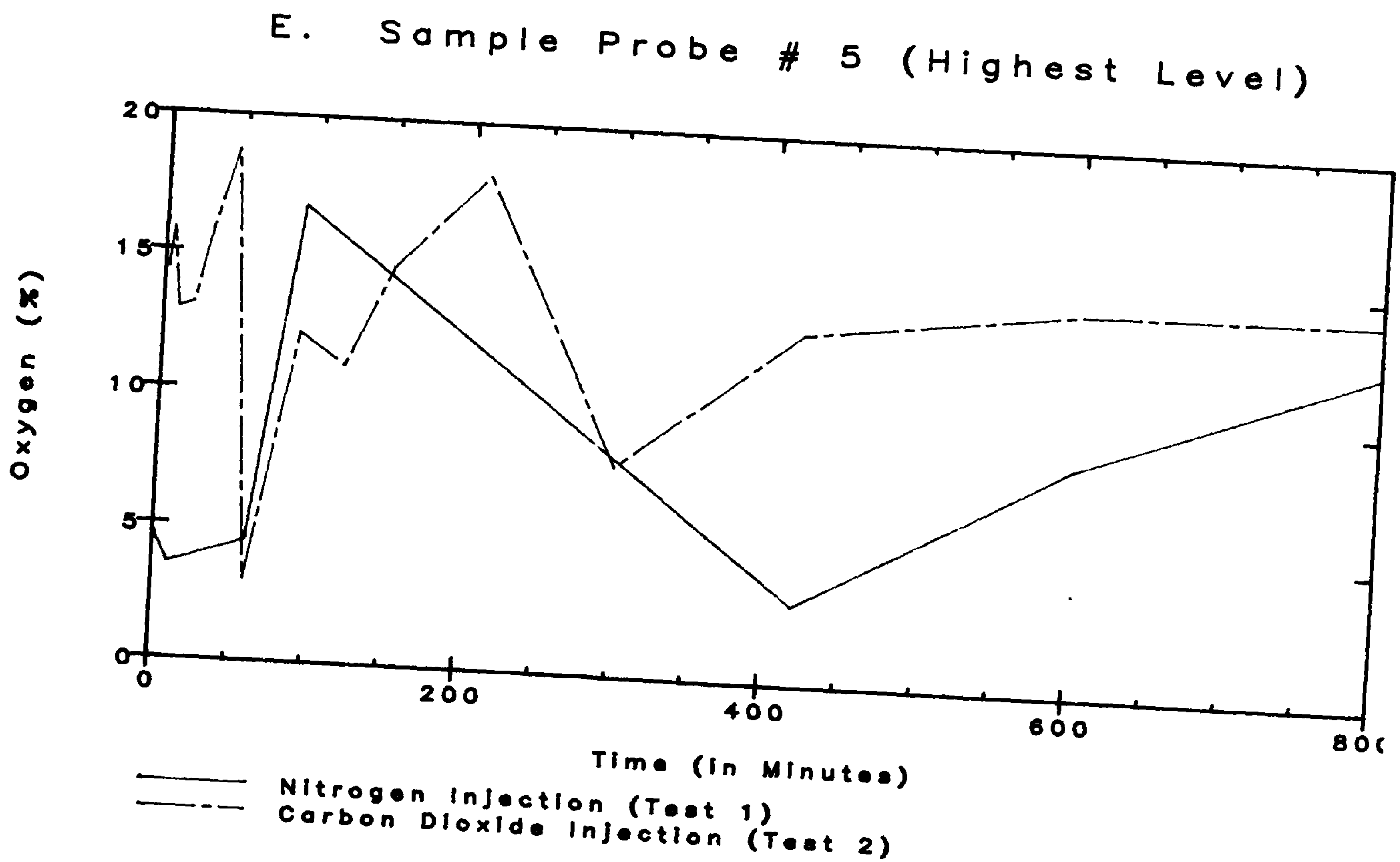


FIGURE 5-7E. COAL COLUMN FIRE EXTINGUISHMENT - CARBON DIOXIDE vs NITROGEN INJECTION (FROM SIDE) - OXYGEN CONCENTRATION - HIGHEST LEVEL

In the lower portion of the column carbon dioxide is the more effective agent. This is illustrated in Figure 5-7 A and B. Sample probe #1, the lowest level, shows that after minute 300, carbon dioxide never allows the oxygen concentration to return to more than 12.5 percent. Test 1, where nitrogen was injected, shows that the oxygen concentration is never reduced to the level that was attained for carbon dioxide injection. For most of test 1, the oxygen concentration remains in the 15-17 percent range. Sample probe #2 illustrates similar results with one notable difference. Although test 2, where carbon dioxide was injected, shows an oxygen concentration reduction to about 5 percent, the oxygen concentration then rises steadily until minute 600 when it levels off at about the same concentration as the oxygen level for test 1, where nitrogen was injected. This shows that carbon dioxide is most effective for the lowest portions of the column, and at these lowest levels, the nitrogen does not appear to have a significant effect.

6.0 SUMMARY AND CONCLUSIONS

For this coal, the spontaneous ignition tests showed that conditions can be made favorable to foster spontaneous ignition. However, the spontaneous ignition events cannot be predicted nor can their locations be predetermined. More importantly, the results could not be repeated.

The permeation studies provided several important findings. The most important was that the retention time for nitrogen was far greater than carbon dioxide. The tests demonstrated that for equal amounts of gas, the oxygen concentration could be kept at a lower level for a longer period of time. Results showed that low gas flow injection rates (for either nitrogen or carbon dioxide) were ineffective. High flow rate injection is required to displace the oxygen. Results also indicated that the position of gas injection is important. The least effective position was gas injection from the bottom of the pile. The side injection position, located at the mid-point of the vertical height, appeared to be the most effective. The top injection point did not appear to permit the gases to penetrate the pile.

The fire quench tests provided the experience needed to create a deep-seated fire. Results from these tests showed that the cooling effects of both carbon dioxide and nitrogen are insignificant in a deep-seated fire situation. Carbon dioxide had a greater impact than nitrogen did but the drop in temperature was only about 7°C (44.6°F) and this was only a temporary drop with the temperature of the fire returning to its original level when the injection stopped. It was not enough to have any significant effect on fire extinguishment.

The coal column fire extinguishment tests confirmed what the permeation studies indicated. The best location for extinguishing gas injection is at mid-height of the column. Results also showed that nitrogen was more effective at maintaining lower levels of oxygen for longer periods of time than carbon dioxide. The only discrepancy was at the lowest level. The lowest level during these fire extinguishment tests showed carbon dioxide to be more effective. Nitrogen did not drop to the lowest two levels in the coal column fire extinguishment tests as it had done in the permeation studies.

It was shown in the spontaneous ignition tests how the rapid depletion of oxygen was the most probable cause for terminating a spontaneous ignition event. In both the fire quench tests and column fire tests, forced ventilation was necessary to create a hot fire. Even with this artificial supply of oxygen it was noted how oxygen poor the gas concentrations were at the start of many of the nitrogen and carbon dioxide injection tests. Therefore, the most effective method for controlling spontaneous combustion is to eliminate the supply of oxygen. Since this is easier done in theory than in practice, the next most effective

method is to displace the oxygen with an inert gas. Both carbon dioxide and nitrogen proved to be effective at displacing oxygen. It can be concluded that for an equal quantity of gas, nitrogen is the more effective agent due to its longer retention time in the pile. Carbon dioxide was more effective at displacing oxygen at the lowest level of the coal column. Carbon dioxide could be as effective as nitrogen if there was no leakage from the bottom of the coal pile. The biggest drawback to carbon dioxide is its tendency to sink due to its higher density.

7.0 RECOMMENDATIONS

Is is recommended that this study be continued by designing a suppression system and evaluating it in full-scale fire tests. This system should be portable with an injection nozzle that can be hand driven 10-15 feet into the coal pile. It is further recommended that this system be designed to be air dropped so that it may be delivered at sea should the need arise. Further study should be done on the volume which the inert gas covers when the gas is injected and on the required frequency and flow rates of replenishment injections necessary for sufficient retention of the inerted atmosphere in the coal pile. It is also recommended that samples be collected from actual spontaneous ignition fires so they can be compared with the data being collected from the experimentally developed fires. Finally, it is recommended that this work be done now in advance of the next energy shortage which would generate increased use of coal and thus lead to crises similar to those discussed in the introduction.

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APPENDIX A

SPONTANEOUS COMBUSTION POTENTIAL OF ILLINOIS NO. 6 COAL AND MODELING OF THE IGNITION PROCESS

SPONTANEOUS COMBUSTION POTENTIAL OF ILLINOIS NO. 6 COAL AND MODELING OF THE IGNITION PROCESS

PREPARED FOR

DEPARTMENT OF TRANSPORTATION

UNITED STATES COAST GUARD

INTERAGENCY AGREEMENT NO. 14-09-0070-1145

By

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Department of Interior

Bureau of Mines

Pittsburgh Research Center

Pittsburgh, Pennsylvania 15236

June 1986

Introduction

The United States Coast Guard and the Maritime Administration are conducting a joint project to identify, test, and evaluate fire prevention and/or suppression techniques for spontaneously induced coal cargo fires on bulk carriers. The Coast Guard (Interagency Agreement No. 14-09-0070-1145) requested that the Bureau of Mines characterize the project coal, evaluate its self-heating tendency, and model the ignition process. In response, the Bureau of Mines performed the following tasks:

1) Obtained data from proximate and ultimate analyses, size analysis, sulfur forms, and heating values to determine the coal type (rank), chemical composition, pyritic sulfur, and particle size.

2) Evaluated the coal's self-heating tendency in the Bureau's adiabatic heating apparatus by determining its minimum self-heating temperature and comparing it to those of other coals previously tested under the same conditions.

3) Developed a mathematical model to predict the heat production and thermal diffusion in a pile of the coal stimulated by an internal heat source of variable size and intensity.

Coal Characterization

Illinois No. 6 seam coal from the Monterey No. 1 Mine, Macoupin County, was selected for the project. One hundred tons of the coal were purchased by the Coast Guard and a 55-gallon drum sent to the Bureau. Surface moisture was visible, and most probably a result of processing and/or shipping the coal. A sample in the as-received state, and a sample which was pulverized and sieved (100 x 200 mesh) were submitted to Geochemical Testing, Inc. for proximate and ultimate analyses, sulfur forms, and heating values. The complete analyses are given in the appendix. Table 1 shows the key parameters obtained in these analyses, as well as those obtained for samples of Pittsburgh seam (Bruceton Mine) and Wyoming No. 80 seam coals. These coals are used for comparison purposes in later sections of this report.

TABLE 1. - Analyses of coals as-received, wt-pct

Coal	Apparent Rank[1]	Heating value, Btu/lb	Moisture	Fixed carbon	Sulfur	Pyritic sulfur	DAF[2] oxygen	Air dry loss
No.6 (as-rcd)	hvCb	10,330	16.2	36.7	3.8	1.2	9.7	11.5
No.6 (100 x 200)	hvCb	10,591	13.1	38.0	3.7	1.2	10.4	11.1
No. 80	hvCb	11,353	11.0	43.9	0.7	0.1	13.5	0.0
Pittsburgh	hvAb	13,947	1.7	53.9	1.3	0.6	7.2	0.0

[1]Based on ASTM D 388 classification system.
[2]Dry-ash-free.

The apparent rank of the No. 6 seam coal, high-volatile C bituminous, is based on the ASTM D 388 classification system.[1] It is similar in composition to the No. 80 coal, also a high-volatile C bituminous, with respect to heating values and fixed carbon content. It has a higher as-received moisture content, although a large percentage of this is surface moisture, as evidenced by the high air dry loss, and a slightly lower dry-ash-free oxygen content. The total sulfur and pyritic sulfur content of the No. 6 coal is considerably higher than that of the No. 80 seam coal. In comparison to the Pittsburgh coal, a high-volatile A bituminous, the No. 6 coal has a lower heating value and fixed carbon content and a higher moisture, sulfur and dry-ash-free oxygen content. These results are expected based on the apparent rank of the coals. In general, the self-heating tendency of a coal increases as the rank of the coal decreases.

The high air dry loss values for the No. 6 coal will have no effect on the laboratory evaluation of the self-heating tendency of the coal, since the coal is dried prior to testing in the sample preparation procedure. However, in large scale tests it could inhibit the self-heating process if the coal is used in the as-received state due to the cooling effect of the evaporation process which will occur during the initial heating phase.

A size analysis of the coal sample sent to the Bureau is shown in table 2. Approximately half of the sample (48.1 pct) was retained on a 4-mesh (470 µm) sieve. Forty-five percent of the sample was through 4-mesh and on 50-mesh (300 µm), while seven percent was through 50-mesh.

TABLE 2. - Size analysis of coal

On	Wt, g	Percent
4 mesh	629.8	48.1
8	199.1	15.2
12	85.8	6.6
20	148.4	11.3
50	154.4	11.8
100	62.6	4.8
200	19.6	1.5
<200	9.2	0.7
	1,308.9	100.0

[1] American Society for Testing and Materials. Standard Classification of Coals by Rank. D 388-82 in 1983 Annual Book of ASTM Standards: Section 5, Petroleum Products, Lubricants, and Fossil Fuels. v. 05.05, Gaseous Fuels; Coal and Coke. Philadelphia, Pa. 1983, pp. 240-244.

Evaluation of Self-heating Tendency

The self-heating tendency of the No. 6 coal was evaluated in the Bureau's adiabatic heating apparatus. Figure 1 is a schematic of the oven and sample container. The oven is designed to maintain the sample and its surroundings at the same temperature. The sample is contained in a wire mesh basket which is enclosed in a stainless steel assembly. Preheated air enters the bottom of the assembly, passes through the sample, and exits at the top. The whole assembly is enclosed in a Dewar flask which provides good insulation.

For a self-heating test, the coal is first pulverized and sieved. The 100 x 200 mesh fraction is then dried in an oven (67° C) under a flow of nitrogen. One hundred grams of the dried coal dust is placed in the apparatus and the sample temperature raised to a preselected value under a flow of dry nitrogen. The sample is then exposed to a 200 cm^3/min flow of moist air, and the thermocouple in the center of the sample records any increase in temperature due to self-heating of the coal. This test is repeated with fresh samples at 5° C increments until the minimum initial temperature from which the coal undergoes a sustained exothermic reaction, or thermal runaway, is determined. This temperature is called the minimum self-heating temperature of the coal.

The Bureau has developed an empirical formula which relates the dry-ash-free (DAF) oxygen content of bituminous coals to their minimum self-heating temperatures (SHT). The formula is:

$$\text{SHT, °C} = 139.7 - 6.6 \times [\text{oxygen, pct(DAF)}] \qquad (1)$$
$$\text{Error} = \pm 10.5 \text{ pct}$$

This expression allows for the prediction of the minimum self-heating temperature of a coal. Using the DAF oxygen content of 10.4 pct (100 x 200 mesh sample), the predicted minimum self-heating temperature of the No. 6 coal was 71° C.

The temperature-time traces of the adiabatic heating tests from initial temperatures of 55° C, 65° C, 70° C, and 80° C are shown in figure 2. In the test at 70° C, the sample underwent thermal runaway and reached a temperature of 186° C in 11 hours with an initial heating rate over the first three hours of the test of 7.9° C/hr. In the test at 80° C, the coal reached 186° C in 6 hours with an initial heating rate of 9° C/hr. This demonstrates the effect of increasing the initial temperature on the self-heating process. In the tests at 55° C and 65° C, the coal reached maximum temperatures of 65° C and 92° C, respectively, before cooling. Although the coal did not undergo thermal runaway in the test starting at 65° C, the coal temperature did increase 27° C. Based on the test results, the experimental minimum self-heating temperature is 70° C.

Table 3 shows the experimental and predicted minimum self-heating temperatures of the No. 6 coal and the Pittsburgh and No. 80 coals. The predicted temperature of 71° C is in excellent agreement with the experimental value obtained. The minimum self-heating temperature of the No. 6 coal falls about midrange between the No. 80 and Pittsburgh coals and indicates the coal has a moderate self-heating tendency. It should be noted that these self-heating temperatures are a relative measure of the spontaneous combustion tendency of the coal alone and do not consider other important contributing factors associated with the spontaneous combustion process in actual mining or storage conditions.

Table 3- Experimental and predicted self-heating results

Seam	Experimental SHT,[1] °C	Predicted[2] SHT, °C	Self-heating tendency
No. 6	70	71	moderate
Pittsburgh	90	92	low
No. 80	45	51	high

[1]SHT - Self-heating temperature; minimum initial temperature from which a sustained exothermic reaction was observed in the adiabatic heating apparatus.

[2]SHT, °C = 139.7 - 6.6 x [oxygen, pct(DAF)].

The effect of moist versus dry air on the spontaneous combustion tendency of the No. 6 coal was also examined in the adiabatic heating oven. Using dry air and an initial temperature of 70° C, the minimum self-heating temperature of the coal, the coal reached a maximum temperature of 73° C in 3 hours before cooling. From an initial temperature of 75° C, the coal underwent thermal runaway, reaching 186° C in 24 hours. Thus there is a 5° C increase in the minimum self-heating temperature using dry air instead of moist air. The temperature-time traces of the tests are shown in figure 3. The results indicate only a small moisture effect on the minimum self-heating temperature of the No. 6 coal under these experimental conditions. The time required for the coal sample to reach 186° C, however, was 14 hours longer when dry air was used even though the initial temperature was 5° C higher.

Further analysis of the temperature-time plots yields rate data that can be represented by an Arrhenius type rate equation:

$$\ln(dT/dt) = -E/RT + \ln A \qquad (2)$$

where E, the activation energy, and A, the preexponential factor, characterize the coal. From a plot of the log of the heating rate versus 1/T, E can be determined from the slope of the line and A from the intercept. A plot of the heating rate versus 1/T for the test using moist air at 70° C, the minimum self-heating temperature of the No. 6 coal, is shown in figure 4. From this plot, the activation energy, E, and the preexponential factor, A, were determined to be

17.0 kcal/mol and 7.5 x 10^6 K/s, respectively. These values were used in the application of the mathematical model that is discussed in the next section.

Development of Mathematical Model

In order to analyze the self-heating of a one cubic meter box of No. 6 seam coal in which a spherical heat source was embedded, such as that used by the Coast Guard in their large-scale tests, a mathematical model was developed that describes the transport of heat by conduction and the exothermic release of heat by oxidation. For the purpose of the model, the bin of coal was replaced by a sphere of one meter diameter concentric with the spherical heat source. The 20.3 cm diameter spherical heat source is either maintained at a constant temperature or as a constant heat flux surface. Both cases are evaluated in this report.

The basic assumptions of the model are that adequate oxygen is available at all times to the pile of coal; buoyancy is not important for low temperature regimes prior to combustion, and what buoyancy there is further circulates the flow within the coal pile due to the mostly closed top on the bin and the coal is distributed uniformly throughout the box. The rate of heat release per unit volume $\dot{q}$, is assumed to follow an Arrhenius rate expression

$$\dot{q} = \rho C_p A e^{-E/RT} \tag{3}$$

where ρ is the coal bulk density; C_p the coal specific heat; A is the preexponential factor; E is the activation energy; R is the gas constant; and T is the instantaneous temperature at a fixed location in the pile of coal. The values used for the calculations in this report are listed in table 4.

TABLE 4. - Physical constants

Constant	Value
λ, cal/cm-K-s	4.8×10^{-4}
C_p, cal/g-K	0.25
ρ, g/cm^3	0.8
A[1], K/s	7.503×10^6
E[1], kcal/mole	17.011

[1]Determined from adiabatic heating apparatus measurements.

The transport and exothermic production of heat are determined by a time dependent transport equation which is written in spherical coordinates,

$$\rho C p \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) + \dot{q} \tag{4}$$

where λ is the thermal conductivity of the coal. Forced convection and buoyancy are neglected in equation (4).

There are two boundary conditions for equation (4). The boundary condition at the outer surface of the spherical pile of coal is for an adiabatic surface,

$$\frac{\partial T}{\partial r} = 0 \quad \text{at } r = R_1 \tag{5}$$

where R_1 is the outer radius of the coal. At the surface of the spherical heat source, of radius R, there are two optional boundary conditions. One is that the surface is maintained at a constant temperature T_1.

$$T\ (r = R_o) = T_1 \tag{6}$$

where R_o is the radius of the spherical heat source. The alternative boundary condition is that heat flow is maintained at a prescribed rate, $\dot{q}''_o$.

$$\dot{q}''_o = -\lambda \frac{\partial T}{\partial r} \quad \text{at} \quad r = R_o \tag{7}$$

Equation (4) was solved numerically subject to the above boundary conditions. Since the largest temperature gradients will occur near the heat source, equation (4) was transformed through an exponential stretch coordinate system that results in a nonuniform grid - fine close to the heat source surface and coarse further into the coal. The resultant partial differential equation was then written in finite difference form, implicit in time, as a set of coupled algebraic equations. Forward time differences and centered space differences were used. The resultant algebraic equations were solved iteratively with the boundary conditions using the Thomas Algorithm. The calculations were continued in time until thermal "runaway" occurred.

For the calculations reported here, the diameter of the heat source was 20.32 cm, and the diameter of the coal mass was 1 m. Two sets of calculations were made. Those in figure 5 show the time for thermal runaway to occur for an isothermal heat source, as expressed by equation (6). In this case the location of the thermal runaway is removed from the surface of the heater, since the isothermal heater also serves as a heat sink once the temperature of the coal exceeds the heater temperature.

Figure 6 shows the time for thermal runaway to occur for a specified heat flux at the heater surface as expressed by equation (7). These results are condensed to a log-log plot.

Figures 5 and 6 should be considered estimates of the time required for thermal runaway to occur in the coal. The assumption of slow ventilation with adequate oxygen supply for continuous self-heating may not be totally correct. Further modifications of equation (4) and the solution techniques would be required.

SUMMARY

The results from the characterization, self-heating evaluation and modeling of the ignition process conducted on the Illinois No. 6 seam coal are summarized below:

1. The results of proximate and ultimate analyses indicate that the coal is a high-volatile C bituminous. It has a high as-received moisture value (16.2 pct) and a relatively high dry-ash-free oxygen value (9.7 pct).

2. A size analysis indicates that about half the coal is greater than 470 µm and 93 pct is greater than 300 µm.

3. The coal had a minimum self-heating temperature of 70° C, indicating a moderate self-heating tendency compared to Pittsburgh and No. 80 seam coals.

4. Using dry air as the test gas increased the minimum self-heating temperature from 70° C to 75° C, indicating a small moisture effect on the minimum self-heating temperature of the coal.

5. A mathematical model was developed that can be used to predict the heating of a confined spherical pile of coal undergoing a temperature dependent oxidation. Heat is supplied to the coal by conduction from an embedded spherical heat source. The model was used to predict the time for thermal runaway to occur in a one meter diameter mass of coal heated by a 20.3 cm diameter heat source.

APPENDIX

GEOCHEMICAL TESTING

COAL, WATER, AND MATERIALS ANALYSIS

R.D. 2, BOX 124

Somerset, Pennsylvania 15501

Phone: (814) 445-6666 or 443-1671

COAL ANALYSIS REPORT

Client: US Bureau of Mines

Date of report: 10/23/84

Description: CG#1
as-received

Lab No. C17589 **

	As-received	Dry	Dry ash-free
PROXIMATE ANALYSIS			
Moisture	16.18		
Ash	10.84	12.93	
Volatile Matter	36.29	43.30	49.73
Fixed Carbon	36.69	43.77	50.27
	------	------	------
	100.00	100.00	100.00
ULTIMATE ANALYSIS			
Hydrogen	6.03	5.03	5.78
Carbon	56.85	67.82	77.89
Nitrogen	1.05	1.25	1.44
Sulfur	3.79	4.53	5.20
Oxygen	21.44	8.44	9.69
Ash	10.84	12.93	
	------	------	------
	100.00	100.00	100.00
HEATING VALUE (BTU/LB)	10330	12324	14154
FORMS OF SULFUR			
Sulfate sulfur	0.02	0.03	0.03
Pyritic sulfur	1.22	1.45	1.67
Organic sulfur	2.55	3.05	3.50

Air Dry Loss = 11.54%

Forrest E. Walker

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Director of Technical Services

GEOCHEMICAL TESTING

COAL, WATER, AND MATERIALS ANALYSIS

R.D. 2, BOX 124

Somerset, Pennsylvania 15501

Phone: (814) 445-6666 or 443-1671

COAL ANALYSIS REPORT

Client: US Bureau of Mines

Date of report: 10/23/8

Description: CG#2
100 x 200 mesh

Lab No. C17590 **

	As-received	Dry	Dry ash-free
PROXIMATE ANALYSIS			
Moisture	13.11		
Ash	11.66	13.42	
Volatile Matter	37.24	42.86	49.51
Fixed Carbon	37.99	43.72	50.49
	------	------	------
	100.00	100.00	100.00
ULTIMATE ANALYSIS			
Hydrogen	5.94	5.15	5.95
Carbon	58.16	66.94	77.32
Nitrogen	1.06	1.22	1.41
Sulfur	3.73	4.30	4.97
Oxygen	19.45	8.97	10.35
Ash	11.66	13.42	
	------	------	------
	100.00	100.00	100.00
HEATING VALUE (BTU/LB)	10591	12189	14079
FORMS OF SULFUR			
Sulfate sulfur	0.02	0.03	0.03
Pyritic sulfur	1.20	1.38	1.59
Organic sulfur	2.51	2.89	3.35

Air Dry Loss = 11.11%

Forrest E. Walker

Forrest E. Walker
Director of Technical Services

LIST OF FIGURE CAPTIONS

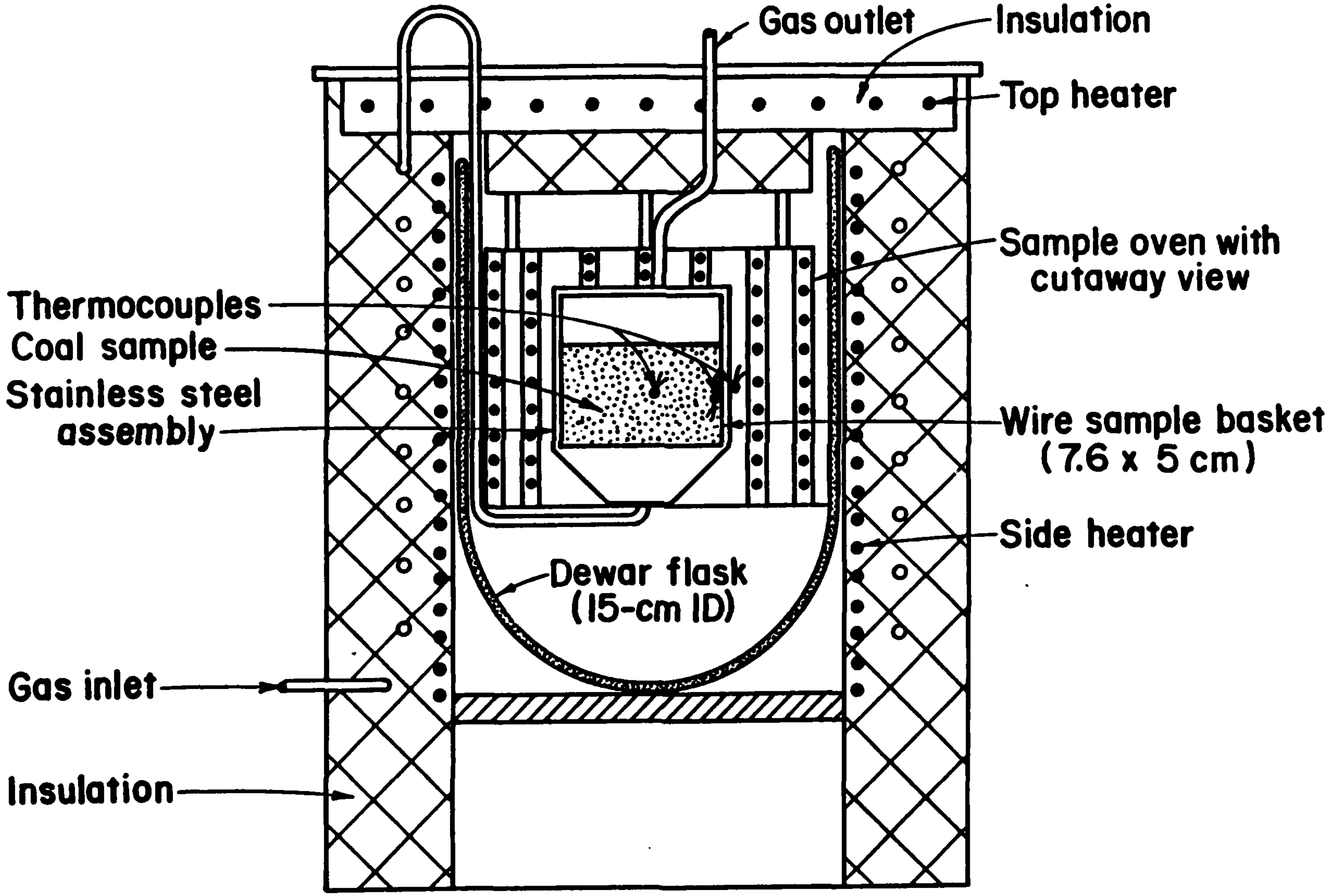

FIGURE 1. - Schematic of adiabatic heating apparatus.

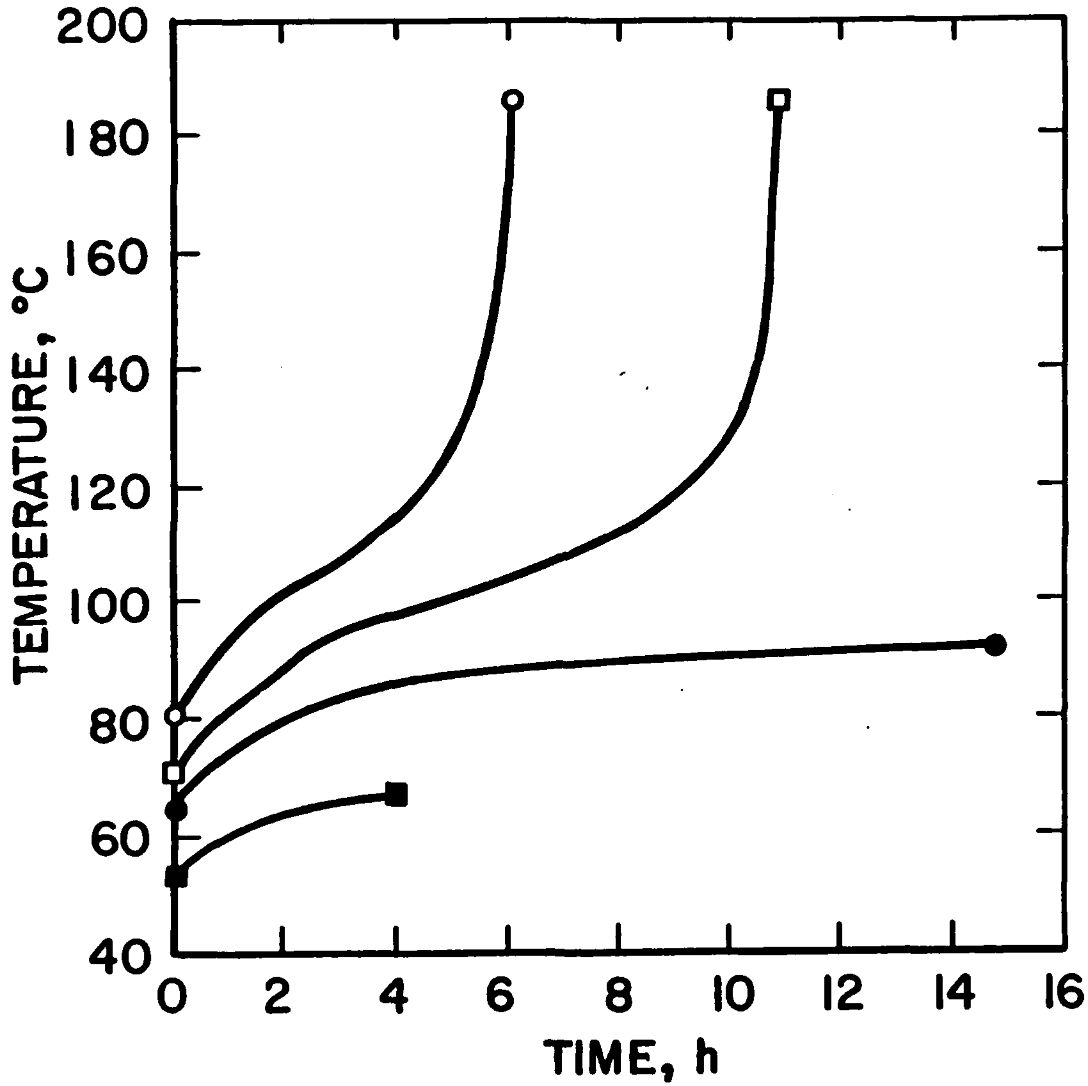

FIGURE 2. - Temperature-time traces in self-heating tests of No. 6 coal from initial temperatures of 55° C, 65° C, 70° C, and 80° C.

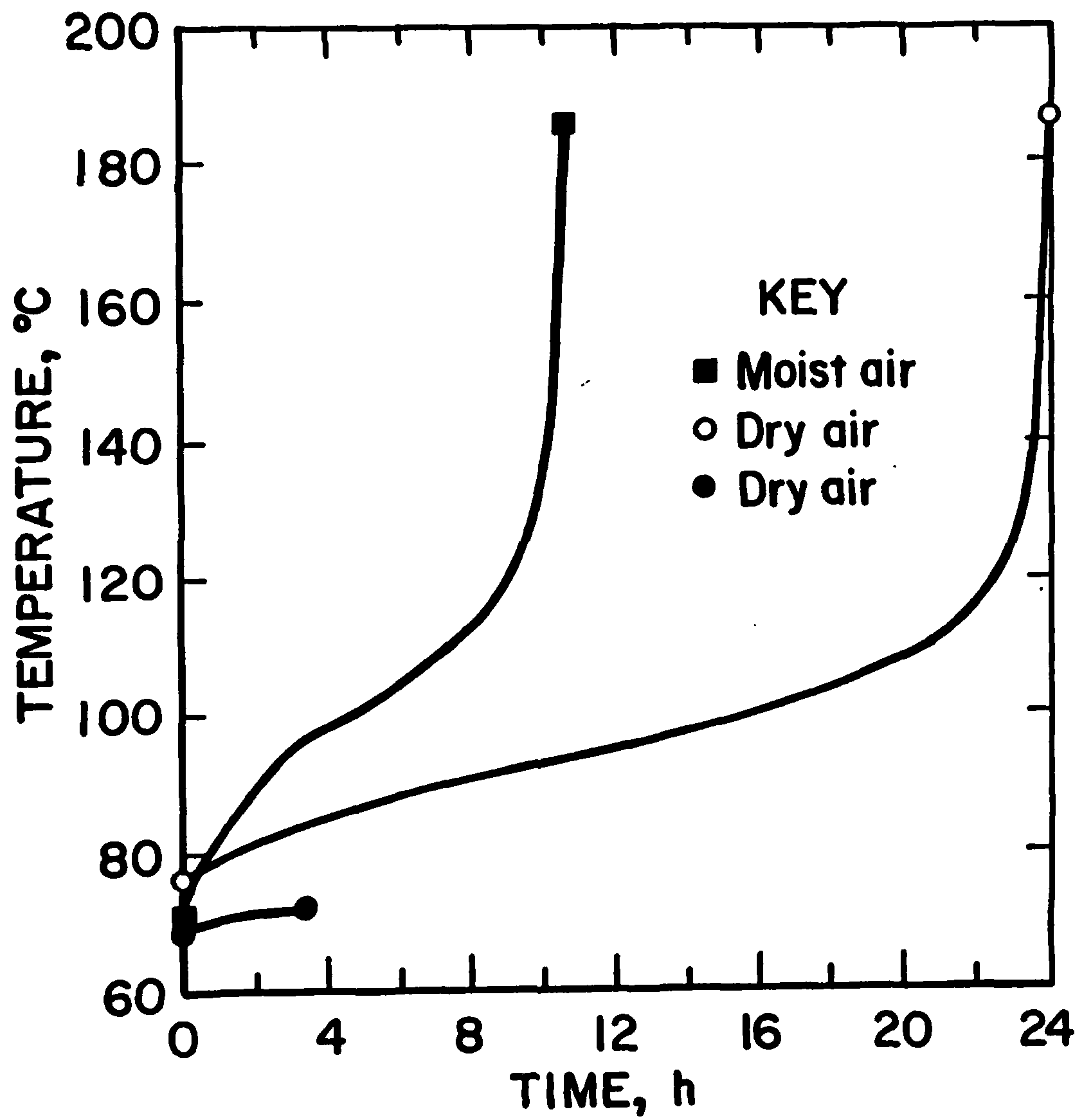

FIGURE 3. - The effect of moisture on the self-heating of No. 6 coal.

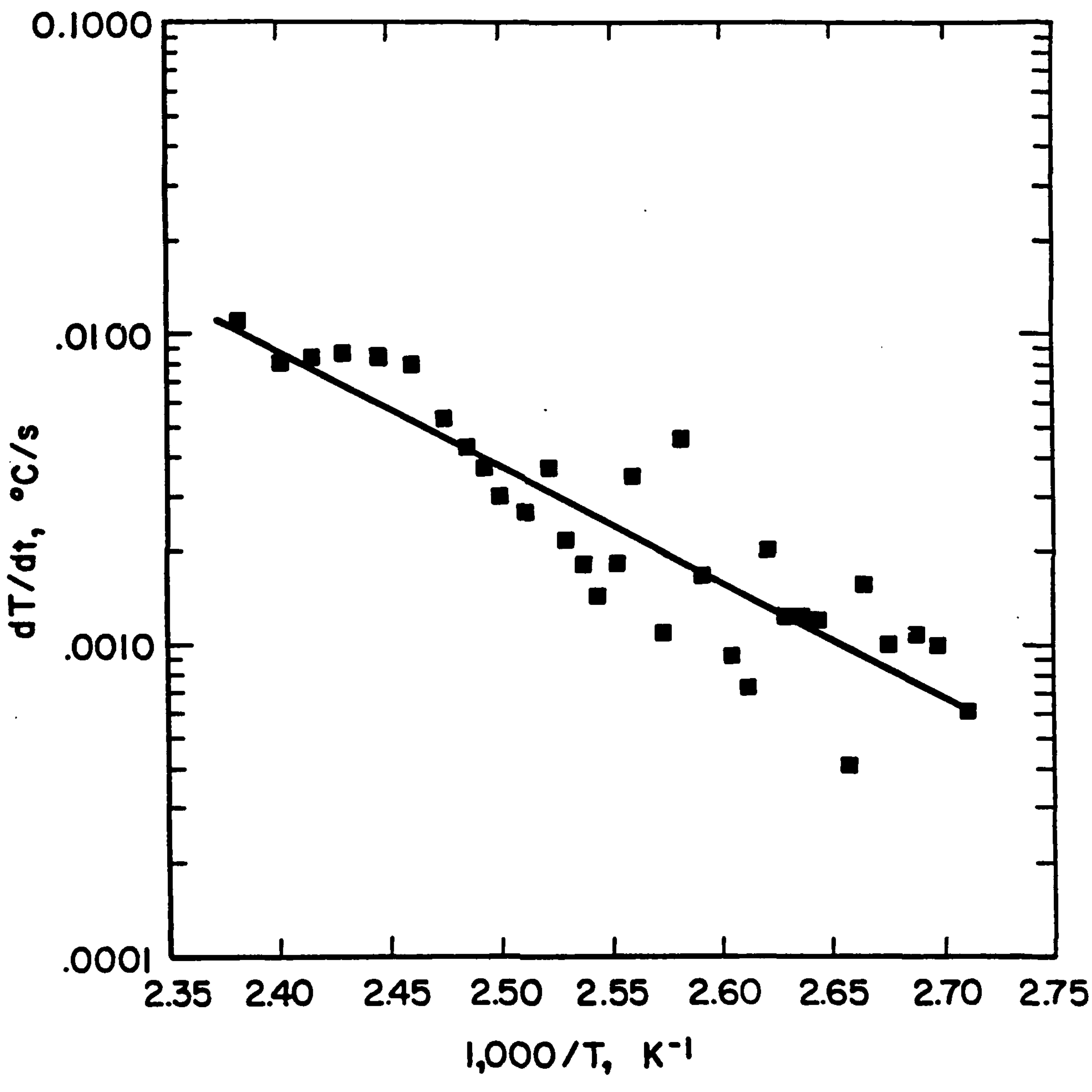

FIGURE 4. - Log dT/dt versus reciprocal temperature for self-heating experiment with No. 6 coal, from 70° C, moist airflow.

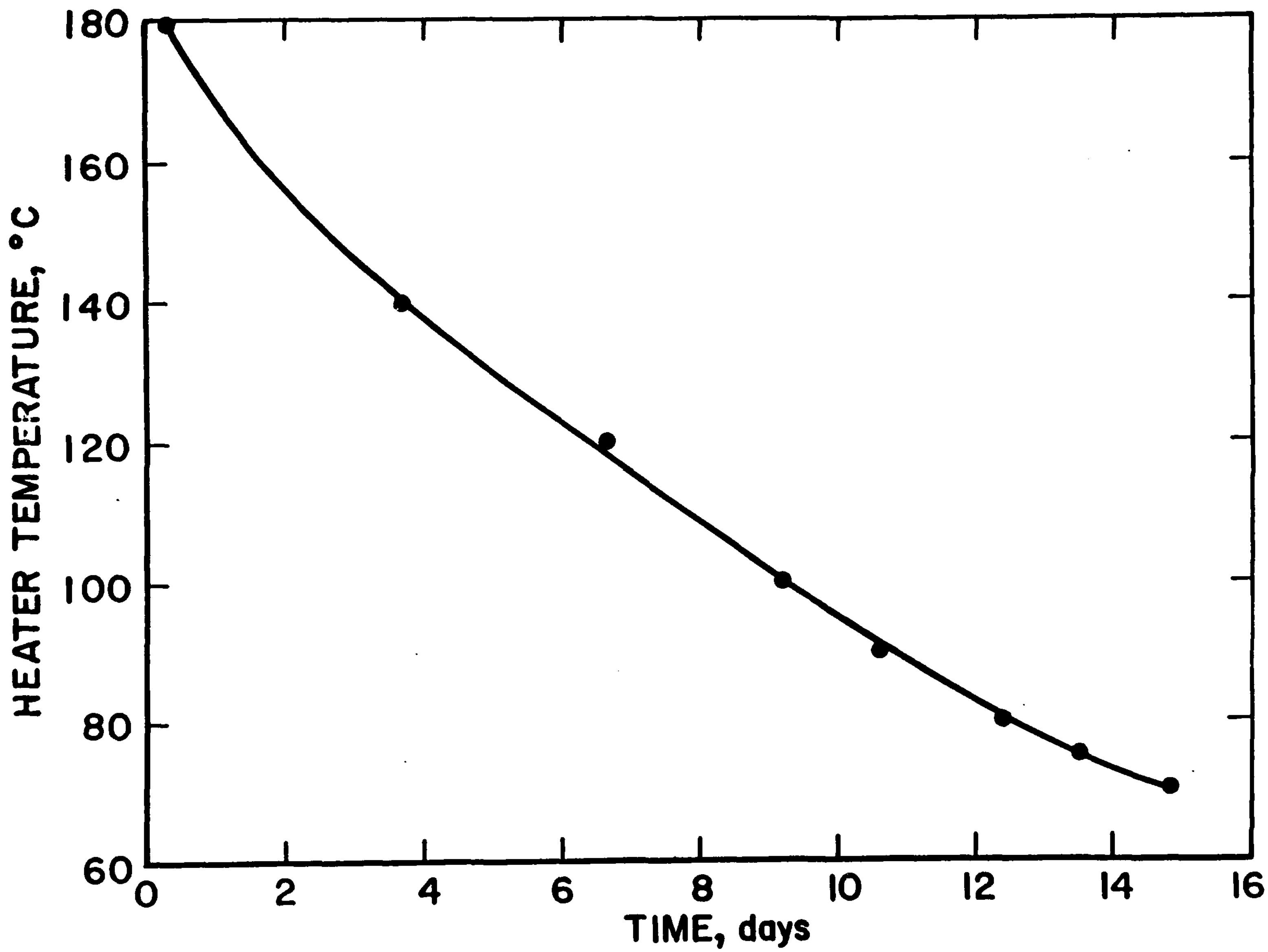

FIGURE 5. - Time for thermal runaway to occur in 1 m diameter coal mass for constant temperature heater.

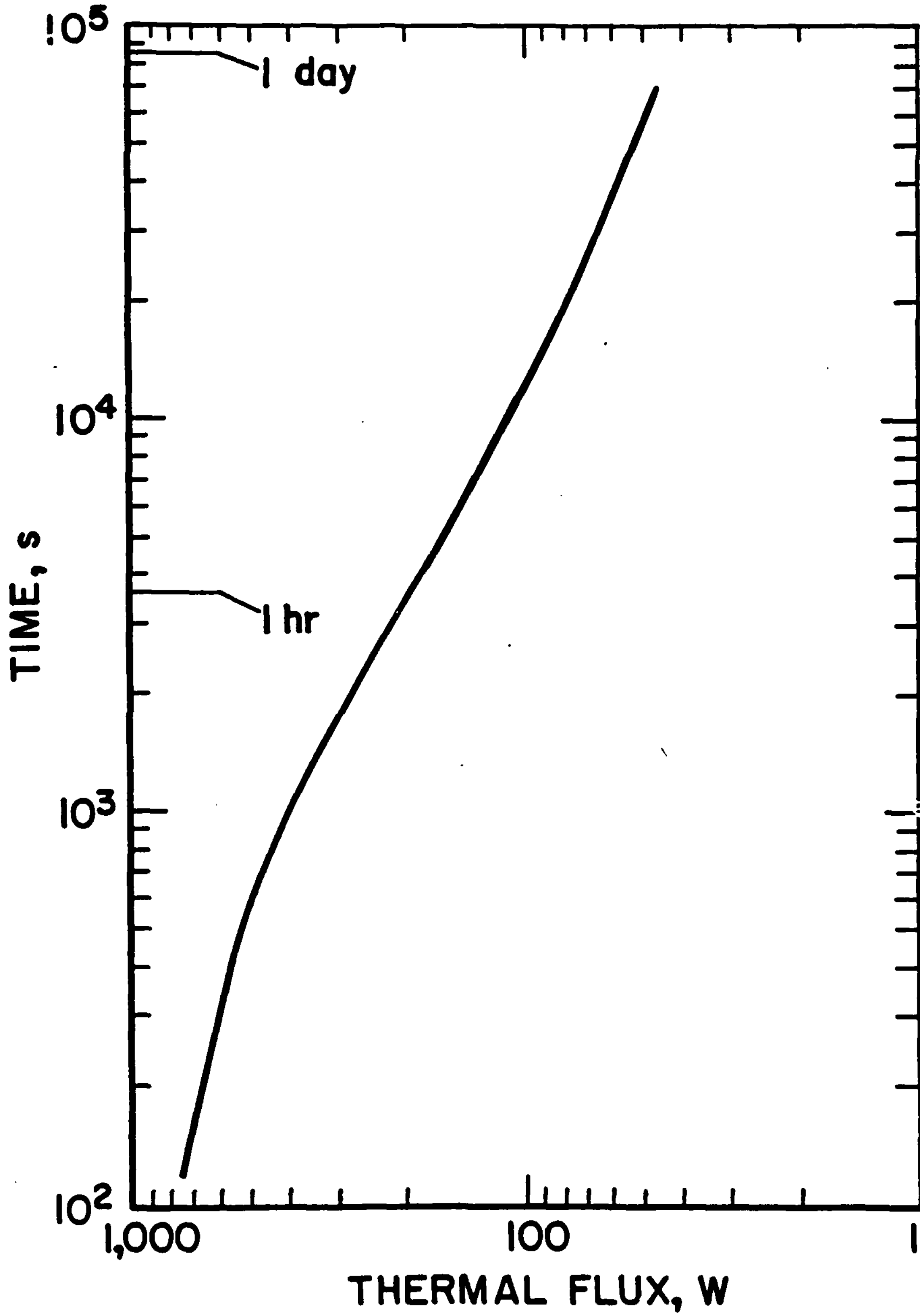

FIGURE 6. - Time for thermal runaway to occur in 1 m diameter coal mass for constant flux heater.